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The analysis of RBMK neutron flux profile distortions using operational data history

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Abstract. In this research the operational data history was analysed. The data set given represents RBMK-1000 parameters for one month of the reactor operation. Axial flux sensors data and channel power data taken from database were considered. The transients of axial and radial-azimuthal neutron flux distributions were visualized. For the flux distribution data from 72 core channels with axial flux sensors the axial offset transients were obtained. In the operational data considered xenon-induced power oscillations were revealed. Phase and amplitude transients of the oscillations were calculated. The dynamics of phase and amplitude were visualized over the reactor core cross-sections. The values of quantities were displayed with different color shades. The iodine-135 and xenon-135 concentrations recovery problem solution was considered. Formulas for concentrations recovery were derived. The recovery procedure obtained is based on Cauchy problem solution calculation process. The dependence of accuracy of the recovered transients on the amount of the available operational data was studied. The dependency graph of calculation error on the amount of operational data was plot. The recovery of xenon-135 concentration was carried out based on the operational data history of the power unit where the phenomenon of xenon-induced power oscillations was observed.

1. Introduction

Space- and time-dependent neutron flux profile distortions in a nuclear reactor may cause various unacceptable effects on thermal-hydraulic parameters and strength of the materials the core consists of. Multiple factors, which affect neutron flux distribution, are usually connected to the reactor operational history – mostly on the reactor's power levels and their changes. The availability of the operational history database allows analyzing and predicting states of an operating power unit [1] and to adapt mathematical models [2] for further numerical experiments with the real-world data. The study of nuclear reactor operational data usually involves the analysis of a system with multiple parameters, which should be properly visualized [3,4].

The problem of periodical flux redistribution is usually connected to the xenon-induced power oscillations. Recent studies [5-8] consider the stability and controllability of nuclear reactors undergoing such phenomenon, as well as the overall in-core flux behaviour, which may consist of fundamental oscillation transient and local perturbations, caused by the control rods. Using the set of operational data history it is possible to examine such transients in detail with help of numerical visualization and to simulate the variety of control procedures applied to a real nuclear reactor state with computer models.



2. Processing and visualizing operational data history

2.1. The data

In this research the transients of axial and radial-azimuthal neutron flux distributions were visualized. For the flux distribution data from 72 core channels with axial flux sensors the axial offset transients were calculated. The operational data set given represents RBMK-1000 parameters for $\Delta t_h = 1$ month of the reactor operation.

Each channel considered contains 4 flux sensors evenly distributed by height. Thus the sum of two sensors' measurements in the top was considered as the integral flux distribution of the top half, the same assumption was taken for the bottom half. Axial offset was calculated as follows:

$$O = \frac{\sum_i \Phi_T^i - \sum_i \Phi_B^i}{\sum_i \Phi_T^i + \sum_i \Phi_B^i} \quad (1)$$

where Φ_T^i – values in the top half of the core, Φ_B^i – in the bottom half.

An example of flux distribution data, extracted for a single channel, is presented in figure 2, see “Flux profile” curve.

Within the time interval observed the oscillations of the flux distribution were occurring. With the use of Fourier transition the properties of axial offset dynamics were analyzed. The spectral density reaches its maximum at $T = 31.2$ h, where T stands for period of oscillations. Such period value and offset amplitude, estimated up to 15%, correspond with the xenon-induced power oscillations phenomenon. The transients derived were processed using the method of moving average with the purpose of cleaning the signal from measurement errors.

2.2. Phase and amplitude transients

To provide more detailed study of the flux shape dynamics, the phase and amplitude transients of the oscillations were calculated. For this purpose the following approach was applied. Let the offset analyzed be expressed as

$$f(t) = A_0 \sin(\omega t + \varphi_0) \quad (2)$$

on interval $[t; t + T]$, where t stands for expression instant, $T = \frac{2\pi}{\omega}$ – period of oscillations, A_0 – amplitude of oscillations, ω – circular frequency and φ_0 – phase shift.

Thus, given ω , scalar multiplications of $f(t)$ by $\sin \omega t$ and $\cos \omega t$ on $[t; t + T]$ give expressions for A_0 and φ_0 at instant t , which were considered as estimations for offset oscillations' parameters.

However, transients analyzed last longer than T ($\Delta t_h = 1$ month) and show continuous oscillations. The aim is to derive continuous phase and amplitude dynamics, which correspond with the original signal. To visualize the process of amplitude and phase change in the operational data history given, time dependencies $A_0(t)$ and $\varphi_0(t)$ were calculated $\forall t \in [0; \Delta t_h - T]$.

2.3. Visualization principles

For each instant in dataset considered the cross-sections of the reactor core were plot (see figure 1), where all of the 72 channels' parameters were indicated. For the better visual perception all of the parameters and their values considered were drawn by different color shades.

The observation of phase and amplitude dynamics additionally allowed noticing the repeating short-term significant changes of the amplitude at different points of the core. The amplitude changes revealed were assumed to be hypothetically related to the refueling of the core. It was concluded based on the time intervals between changes. To verify the hypothesis the refueling schedule was recovered from the operational data history for the time interval considered. The algorithm of refueling instances detection was implemented, which classified the discontinuities of energy emission transient as the subsequence of refueling. For the subset of refueling instances it was shown that the local short-term amplitude growth actually takes place in the proximity of a channel being refueled at the same time. In

addition it was noted that the short-term amplitude growth causes wave spreading corresponding changes in the surrounding channels. Such behavior may be connected to the subsequent control rods movement.

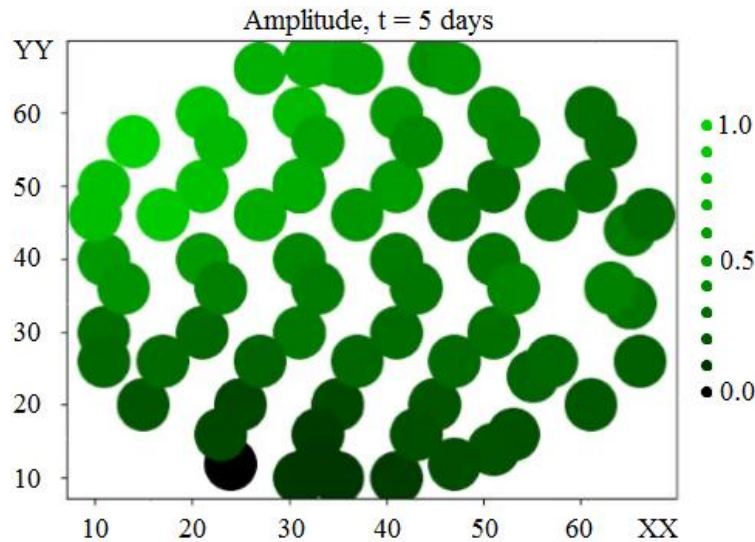


Figure 1. An example of the RMBK core cross-section image. The quantity imaged is amplitude of xenon oscillations divided by the maximal amplitude value within the considered time-interval, the values imaged are calculated at $t = 5$ d. Each circle represents one of 72 channels, “XX” and “YY” stand for channel coordinates, shades of green indicate the growth of value from darkest to lightest shades.

3. Recovery of axial xenon-135 distribution dynamics

Neutron flux field optimal control under xenon-poisoning problems involve solving the system of ordinary differential equations. It's necessary to have initial conditions to derive the particular solution of the system, which are the initial concentrations of xenon-135 and iodine-135 nuclei. Apart from specific situations they are considered to be equal to steady-state corresponding values. With use of operational history database it is possible to recover the real-world values of concentrations at the particular moment, when it is decided to apply optimal control problem solution. For instance, optimal reactor start-up after short-term shutdown may be the context of interest.

3.1. Concentrations calculation

The data from neutron flux sensors and the channels' power calculation results for the time period of one month were extracted from the operational history database [3]. The data extracted represents several channels at different areas of the core.

A one-point model of xenon-135 and iodine-135 concentrations dynamics was used for the recovery experiments. The model used is expressed by differential equations system of the following form:

$$\begin{cases} \frac{dI}{dt} = \gamma_I \Sigma_F \phi(t) - \lambda_I I(t) \\ \frac{dX}{dt} = \lambda_I I(t) - \lambda_X X(t) - \sigma_X X(t) \phi(t) \end{cases} \quad (3)$$

where t stands for time, I and X stand for iodine and xenon concentrations, $\lambda_{I,X}$ – their decay constants respectively, γ_I – fission products yield, Σ_F – uranium-235 macroscopic cross-section, σ_X – xenon microscopic cross-section for thermal neutrons, ϕ – thermal neutron flux. The neutron flux time dependence acts as the control for the system of differential equations in terms of mathematical control theory.

Given initial conditions $I(t_0)$ and $X(t_0)$, their combination with the system (3) represents the Cauchy problem. The solution of the problem is expressed as follows:

$$I(t) = I(t_0)e^{-\lambda_I(t-t_0)} + \int_{t_0}^t e^{\lambda_I(\tau-t_0)} \gamma_I \Sigma_F \phi(\tau) d\tau \quad (4)$$

$$X(t) = X(t_0)e^{-\int_{t_0}^t (\lambda_X + \sigma_X \phi(\tau)) d\tau} + \int_{t_0}^t e^{\int_{t_0}^{\tau} (\lambda_X + \sigma_X \phi(\xi)) d\xi} \lambda_I I(\tau) d\tau \quad (5)$$

As follows from the form of the solution, to calculate xenon concentration at any instant the values of t_0 , initial conditions, flux on $[t_0; t]$ interval and physical constants are required. The latter are known tabular values for the model considered, flux values are taken from the operational history database, but initial conditions and instant t_0 remain unknown. Since the problem assumes the recovery of xenon concentration at any instant t , let the reactor model be considered at instants $t \gg t_0$. Then both initial conditions tend to zero, so formulas take the following form:

$$I(t) = \int_{t_0}^t e^{\lambda_I(\tau-t_0)} \gamma_I \Sigma_F \phi(\tau) d\tau \quad (6)$$

$$X(t) = \int_{t_0}^t e^{\int_{t_0}^{\tau} (\lambda_X + \sigma_X \phi(\xi)) d\xi} \lambda_I I(\tau) d\tau \quad (7)$$

It is obvious that after the simplification the only unknown parameter is t_0 , which practically defines the amount of operational data history used for calculation.

Thus, the recovery of concentrations at the given instant represents a Cauchy problem solution calculation, where the end points of resulting transients are the values to be recovered. The size of the solution interval depends on the time period, on which the operational data history is available.

To recover xenon concentrations, neutron flux absolute values were calculated based on the known power of the channel given. The values obtained were used to process the axial neutron flux sensors data and to calculate the actual axial flux values.

The concentrations of xenon and iodine were recovered for the given period of time with the procedure considered. The example of a transient recovered compared to its corresponding flux profile transient is represented in figure 2.

The recovered xenon-135 concentration transient was experiencing antiphase oscillations with the same period. Such behavior is caused by the nature of xenon poisoning phenomenon and is shown in other works on this topic [5,9,10], thus verifying the adequacy of the procedure used.

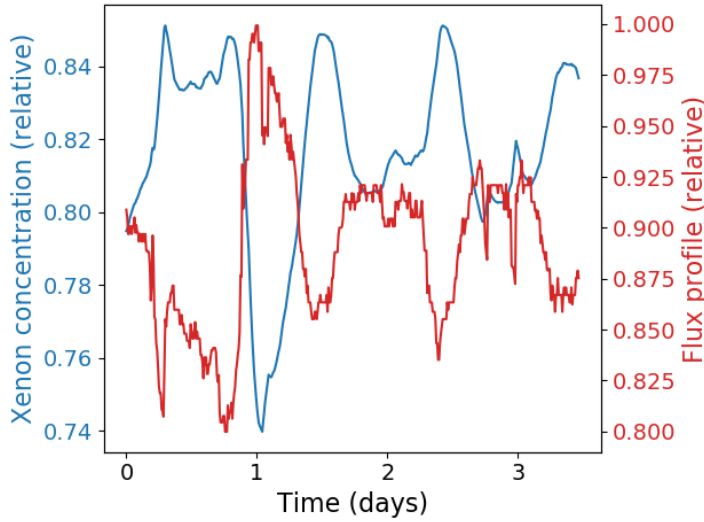


Figure 2. The dynamics of the flux profile given and xenon concentration recovered based on the flux profile.

3.2. Recovery accuracy

The dependence of the recovered transients on the amount of the available operational data history was studied. Let $\Delta t = t - t_0$ represent the amount of operational data history. According to (7), recovered X is actually the function $X(t, \Delta t, \phi)$, where t defines the instant of recovery, Δt defines the interval $[t_0; t]$ as well as the amount of operational data history and ϕ is the data itself in form of flux function defined on $[t_0; t]$. As the measure of recovery accuracy the error function was introduced to investigate the influence of the operational history size on the calculation result:

$$E(\Delta t_1, \Delta t_2) = E(t, \Delta t_1, \Delta t_2, \phi) = \frac{X(t, \Delta t_2, \phi) - X(t, \Delta t_1, \phi)}{X(t, \Delta t_2, \phi)}, \Delta t_2 > \Delta t_1 \quad (8)$$

where t value is fixed for all recovery results to be compared, as well as ϕ , which is defined on $[t - \Delta t_2; t]$ using the same dataset for all recoveries compared. Error function of such form evaluates the difference between two recoveries based on different amounts of data history in percent. The value of Δt_2 may be fixed at the overall duration of data history available and Δt_1 may vary for comparison purpose.

The dependency graph of calculation error on the size of operational data history was plot (figure 3) for $\Delta t_2 = 2$ weeks. The recovery of xenon-135 concentration was carried out based on the operational data history of the power unit where the phenomenon of xenon-induced power oscillations was observed.

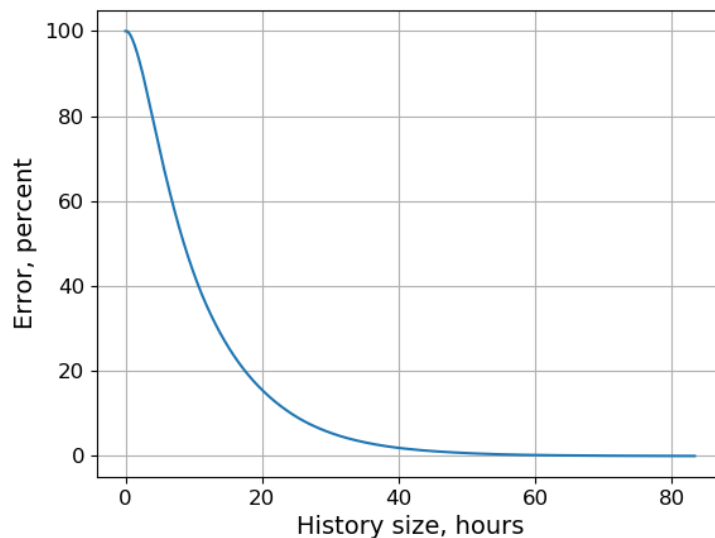


Figure 3. The dependence of the error (in percent) between the recovered xenon-135 value based on two weeks of history and another value recovered by lesser history on history with duration T .

4. Conclusion

The present study concludes, that the analysis of nuclear reactor operational data history with use of appropriate mathematical methods may produce novel scientific and practical results. Thus, the set of operational data considered allowed to demonstrate how xenon-induced power oscillations may be studied and to observe amplitude and phase change over time due to in-core control procedures during such oscillations. Besides that, the xenon-135 concentration recovery procedure was implemented, thus allowing to carry out further numerical experiments with real-world nuclear reactor state.

This research may perform as the starting point for further studies of nuclear power plants control, security and economy. One of the possible consequent results is the development of the computer expert system for xenon oscillations damping, based on the real experience of nuclear power plants' operating personnel [11]. Also the approaches described allow adapting computational models to the operating state of the given power unit thus helping to choose appropriate constraints and criteria for optimal control problem statement [12,13] and to obtain a control strategy suitable for the situation.

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