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A. D. Skorbun[1], S. M. Stadnyk[1], V. G. Kotelenets[2], O. L. Arvaninov[2], A. V. Drobetskii[2]

Institute for Safety Problems of Nuclear Power Plants, NAS of Ukraine, Kirova str., 36a, Chornobyl, 07270, Ukraine
[2] Separated department «South-Ukraine NPP» of the state enterprise «NNEGC «Energoatom», Mikolaiv oblast, Yuzhnourainsk, 55000, Ukraine

COMPARISON OF STATISTICAL PROPERTIES OF COOLANT TEMPERATURE AND NEUTRON FLUX IN A REACTOR PWR-1000

Using wavelet analysis an existence of regularities in “noise” signals from neutron flux detectors and temperature ones of a design in-pile control system of PWR-1000 reactor was investigated. For the purpose to check the possibility to estimate coolant parameters through neutron flux parameters and vice versa, a comparative analysis of statistical characteristics for parallel long regular sets of measurements of coolant temperature and a neutron flux was carried out. It were analyzed neutron signals from three measurement canals with ionization chambers, and from temperature sensors for coolant of the cool and hot branches of the first contour. In both variables a rich spectrum of various long time (tens of minutes and hours) periodicities has been revealed. Some of them are found both in temperatures and in the neutrons flux. It was however revealed also periodicities, which in neutrons and in a coolant do not correlate between themselves. The differences between the pictures of wavelet transform of temperatures of hot and cold branches of the first contour have been shown. In the temperature of hot branch additional more high frequency vibrations, which can be ascribed to development of turbulence, are arisen. The conclusion was drawn, that fluctuations of signals, that have been analyzed, are not random noise, but are the data carrier about neutron subsystem of a reactor. It is suggested to carry out the analysis of fluctuations of signals of a design in-pile control system for early detection of a reactor operating conditions.

Keywords: nuclear reactor, neutrons, coolant, noise statistics.

Introduction

In the theory of nuclear reactors it is generally known [1], that between the state of a coolant and neutron field there is nonlinear connection – in dependence on pressure, temperatures and other factors, probability of moderation of neutrons changes, that in turn causes changes in probability of fission processes and energy release. Among them boiling of water, that is appearance in it vapor bubbles, especially influences on the value of such connection. Methodology of detecting of boiling processes in PWR reactors [2, 3] is based on such connection, where it is suggested to draw conclusion about the presence of boiling on the increase of dispersion of neutron flux noise.

Thus at now neutron flux fluctuations are connecting with fluctuations of coolant parameters, and beginning of boiling it is proposed to detect through control the value Δ – relation of dispersion of a neutron flux noise to its mean value [2]. On the assumption of this, in the given work in-depth statistical analysis of noises of neutron detectors signals has been carried out with the purposes to reveal other possible parameters of these signals, which would characterize connection of the neutron subsystem with a coolant.

With that end in view the sets of measurements of coolant temperatures and neutron flux, which were carried out simultaneously, have been analyzed. These data are received as a result of regular measurements of mentioned parameters with the design devices of the in-pile control system. The task was given to show, how much the changing of these parameters in time are interconnected.

Because to make purposeful experiments in a reactor is practically impossible, the results, which were received in a given work, are compared with the results of [2], which are based on special experiments. In [2] the next assertion were formulated, which can be checked on real data:

1. When boiling appearing, dispersion of neutrons noises is increasing. At this the value of a neutron flux proper can be not changed.

2. The pointed changes are fixed, when amplitude of coolant temperature fluctuations at input in a reactor exceed approximately 0.2 °C.

3. The effect (a value of Δ) is maximal when frequency of fluctuation is in the region of 0.5 Hz (the result of model calculation with NOSTRA code and comparison with an experiment).

Experimental data and methods of analyzing

In the given work signals from control equipment of the system of in-pile control, which were received during the work of the reactor facility PWR-1000 in steady-state conditions at nominal power, were analyzed. That is for receiving such information it’s not necessary to use the additional special equipment.

Data. Due to a comparative analysis of changing of coolant temperature and neuron flux was planned to carry out, than data of measurements from two systems have been analyzed.

1. Signals of an equipment for neutron flux control from three measurement channels 1, 8, 15 (which in what follow will be named K1, K8, K15), which are shifted on 120^o relative to each other in a cross-section of a reactor (Fig. 1 see cover page 2). At nominal power devices for neutron flux detecting (ionization chambers) work in a current mode, and each channel performs information acquisition and treatment for signals from two blocks of neutron flux detecting (BDNF): lower – BDNFl, and upper – BDNFu. These detecting blocks (for all three channels) are placed approximately on equal height relative to the middle of a reactor core. Integrated data from BDNFl and BDNFu are the data from one channel. Thus, it is analyzed an information, which is sufficiently averaged over reactor core volume.

2. Signals from temperature sensors, which are placed at the input and output of a coolant from a reactor core:

YA21T31 – coolant temperature on the outlet from a reactor the second branch of the main circulation contour (measuring tool – a resistance sensor);

YA22T32 – coolant temperature on the input in a reactor the second branch of the main circulation contour (measuring tool – a resistance sensor).

Analyzing methods. The main task, on the analogy of [2], was to search correlations between changes of temperature and neutron fluxes with the aim finding possibilities of an early diagnostics, at the expense of use special sensitive methods of analyzing. In this work it was supposed, that it is easier to find correlation, analyzing periodical signals. About existing of such periodicities in many sensor it had known [4].

For searching periodicities a wavelet analysis was used, with the help of which it is possible not only to reveal a periodical phenomena, but also clear to fix intervals of time, when they arise and disappear, a shift of the signals in a time between different detectors and so on [5, 6, 7]. Gaussian wavelets of 2-th and 10-th orders were used as very convenient to reveal periodicities. The result of wavelet transform is a two-dimensional matrix of coefficients, the value of which will be maximal, when a function, which is analyzed, will contain corresponding frequencies.

This matrix can be represent graphically, where on horizontal axis of this two-dimensional image the consecutive number of an array element is drawn (at sampling periodicity in one second it will be simply time in seconds), and along vertical axis the so called scale of wavelet, which is proportional to period, is drawn. The values of wavelet coefficients can be drawn in colors or shades of gray. If "noise" signal during some time interval contains sinusoidal component, then in image of wavelet coefficients a series of regular "spots" will appear, the position of which will corresponds to maximums and minimums of this sinusoid.

The data from BDNF were recorded with sampling period $T_p = 1$ s, and sampling of temperature was carried out at $T_p = 0.67$ s. Thus, in contrast to measurement, for instance, vibration frequencies with special devices, in our analysis the frequencies, greater than $1/T_p$, cannot be revealed.

Results and discussion

It turned out, that frequency-temporal structure of fluctuations of analyzed signals is enough rich and therefore cannot be represent in one image in details. Therefore two different situations were examined separately: short-period and long-period processes in the same signals. This gives the possibility, using "microscopic" abilities of wavelet analysis [6], to demonstrate periodicities in a wide range of frequencies.

Long-period processes

Fig. 2 (see cover page 2) shows the results of wavelet transformation of the neutron flux density signals for all three channels: K1, K8, and K15 in the units of nominal power (% N_{nom}). In the upper part of each figure there is a graph of changes in the neutron flux density over time. Two-dimensional picture is the result of wavelet transformation of this signal. On the horizontal axis, the consecutive number of the element of a series of measurements is marked. Since the sampling is regular and goes with intervals in one second, then for neutrons the horizontal axis is a time from the beginning of measurements in seconds. On a vertical axis the period is set in units of the values of the horizontal axis. Exactly the period of spot series can be determined using software as the distance between the spots. The duration of the measurements was about 30 000 s, that is, more than 8 hours.

In the behavior of the neutron flux density one can see the following. 1. In addition to fluctuations from about 99.8 to 101 (% N_{nom}) there is a trend: the signal gradually decreases, then increases. 2. Also, there are quite sharps jumps of the signal (shown by the arrows in Fig. 2b) (see cover page 2). The reasons for such behavior of the neutron flux are not discussed at present. 3. For the analysis, we have specially chosen the time interval at which these features are observed in order to demonstrate the capabilities of the method for our task: to record both the appearance of features in the neutron flux and their manifestation in the results of wavelet transformation.

In pictures of wavelet transforms of neutron signals one can see the following. 1. Pictures in general have the same appearance for all three channels. 2. In all of the pictures there is a series of three large spots (indicated by the arrows in Fig. 2a) (see cover page 2) This means the existence in the signal a periodical component with a half-period, which is equal to the distance between two adjacent spots. It is programmatically possible to determine the position of these spots, the distance between them and thus to calculate the period, which turned out to be approximately 7.2 hours. 3. The position of the spots on the horizontal axis is the same for all three graphs, that is, within the accuracy of the measurements, time shift is no detected between them. As a minimum, this means that the field of neutrons in the volume of the reactor core on such time intervals changes more or less same.

Fig. 3 (see cover page 2) shows the results of wavelet transform for cold branch temperature (YA22T32 sensor) and hot thread (YA21T31 sensor) of coolant. This makes it possible to directly compare the pictures of the wavelet transform for neutrons and for temperatures. The first thing to note is that in the signals for both temperatures and in a neutron signal periodicity of 7.2 hours is presented also (three large spots in the lower part). Secondly, that in the wavelet transform of the temperature of the hot branch there is a high-frequency component which is absent both in neutrons data, and in the temperature of the cold branch. This effect is appeared as black random structure in an upper part of the image. Upper part of the image for cold water is gray in contrary. And the third thing to note is that the temperature curve of the cold branch resembles (trend and jumping) the neutron behavior pattern. At the same time, for the temperature of the hot branch, the jump in the center is barely noticeable, and the trend is not visible to the naked eye, although wavelet transform clearly marks out these features.

Thus, from the comparison of the results of wavelet analysis of signals from neutron sensors and temperature sensors, one can conclude that the noise component of these signals contains the same information about the periodicity, hidden in them. Particularly clear correlation manifests itself when comparing the neutron signal and the temperature of the cold branch of the coolant. In turn, this suggests that the fluctuations of the analyzed signals are not random noise, but reflect the dynamics of the corresponding parameter (neutrons or temperature), since otherwise there would be no correlation found.

In [2] by the calculation method it was shown that the change in the dispersion of the noise neutron signal is noticeable (statistically with the given reliability) when the coolant temperature changes at the reactor input at 0.2 - 1 °C. This is a fairly noticeable value, since (Fig. 3 see cover page 2), in the normal mode of operation, at small intervals of time, temperature fluctuations are observed in the region of < 0.1°C for cold branch, and < 0.4 °C for hot branch. The graphs show, that large-scale 7.2 hours trend gives only 0.1 °C for a cold branch, and without this trend the value of fluctuations are even smaller. And just the 7.2 hour trend appears in the form of large spots on a two-dimensional picture. If on the graph for neutrons the trend is observed with the naked eye, then at the temperature, especially hot, it is not so. However, wavelet analysis easily detects it in all cases. That is, the sensitivity of this method of analysis is much higher. This allows us to hope that the appearance of boiling can be fixed at much earlier stages.

Consequently, it can be assumed that in this paper it is shown experimentally that there is a correlation between the behavior of the fluctuations in the temperature of the cold branch and the neutrons fluctuations. Thus, it is directly shown that the fluctuations of these signals carry the same information as the changes in the dispersion of the signals, used in [2].

Short-periodic processes

It must be emphasize that the above shown two-dimensional pictures are only a graphical representation of the general two-dimensional matrix of coefficients of the wavelet transform, and any parts of this matrix of the transform can be analyzed separately. That is, all the information shown in Fig. 4 (see cover page 3) on the cover there was also in Figs. 2 and 3 (see cover page 2), but hidden due to incomparability of the corresponding coefficients of the wavelet transform.

It was suggested at signals analyzing, that the reactor work in a design mode and boiling is absent. But it should to notice, that in a reality on a given time instrumental methods for control of boiling presence are absent. In Figs. 2 and 3 (see cover page 2) we see a correlation in changing of temperature and neutrons with time. But observed period in 7 hours is too big to detect such a phenomenon as boiling, and to take measures. Therefore, the question arises: can one see something in a shorter period of time and for what period of time to calculate, say, Δ?

To do this, we will analyze our data sets, for example, in the first 10 000 seconds, to avoid, at the same time, the manifestations of a leap of values in the middle of the sets and to analyze only statistical fluctuations. The results are shown in Fig. 4. (see cover page 3) In these figures, first, it is clearly seen that the signals of both temperature and neutrons have a rich internal structure and are therefore not accidental in the statistical sense of the word. Recall that regularly located series of spots mean the occurrence and disappearance of periodicities with sufficiently big amplitude. Such series of spots in Fig. 4 (see cover page 3) exist at different times and on different scales.

Secondly, although such periodicity is apparent on both graphs (both for neutrons and for temperature), however, careful consideration of drawings, and careful analysis with software shows that only long time periodicities are common for the analyzed signals.

But there are other interesting peculiarities. Thus, temperature has clearly apparent spots series with period about 5700 c (shown by the red rectangle), that is about 47 min. All other spot series for hot branch have a behavior, more inherent to random data. The cold branch on the scale about 500 sec has a clear periodicity, which correspond to ~ 5 min period (green rectangular). Thus, long time periodicities are revealed both in neutrons and in temperatures. But more high frequency oscillations, which are revealed in temperatures, are not connected with neutron ones (yellow rectangle).

Thus it is revealed, that in the fluctuations both neutrons and temperatures there are enough noticeable oscillations, which are interconnected only partially. If the temperature fluctuations can still be a priori associated with the turbulence of the flow, that always exists [8], and may occur regardless of the existence of the neutron (see [9] and the references therein), then for the occurrence of oscillations in the density of the neutron flux there should be a nonlinearity, which today is tied to a nonlinear relationship with the parameters of the coolant-moderator. And, consequently, between their changes in time there should be connection, that is observed only in long time oscillations.

An explanation of why there is no link between the oscillations in the density of the neutron flux and the temperature (Fig. 4 see cover page 3) can be the finite sensitivity of the characteristics of this process: in order for the connection manifests, there should be sufficiently large changes in the state of the coolant, which are estimated in [2] as more than 0.5 °C, which is not so in our experiment. But then, that is in the absence of a correlation between the behavior of neutrons and the temperature of the coolant, it is necessary to look for other causes of the oscillation in the neutron field. For example it can be assumed, that in reality there is a low amplitude chaotic regime, which is normal even at the regular mode of operation of the reactor, or purely neutron effects like xenon oscillations, but with a much smaller period and amplitude.

Conclusions

1. Using wavelet analysis, it is shown that the fluctuation component of signals from temperature and neutron fluxes standard sensors, at the regular mode of operation of the PWR-1000, contains a variety of information about the dynamics of these parameters in time.

2. It is shown that the various patterns found in the analyzed signals are a reflection of the dynamics of the corresponding parameters, but not the random noise.

3. It was found that changes in the temperature of the cold branch of the first contour, at a magnitude of these changes of about 0.1 °C, correlate with changes in the density of the neutron flux.

4. It was revealed also numerous irregular periodicities in the signals of both temperature and neutron sensors, which do not correlate with each other.

5. It was shown that the sensitivity of the applied analysis method for detecting changes in the signals is much higher than the simple estimate of the changes in the magnitude of the dispersion of the signal fluctuation component. This allows us to offer a wavelet analysis of parallel measurements of the temperature and the neutron flux density to control the appearance of boiling of the coolant.

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А. Д. Скорбун[1], С. М. Стадник[1], В. Г. Котеленець[2], О. Л. Арванінов[2], А. В. Дробецький[2]

[1]Інститут проблем безпеки АЕС НАН України, вул. Кірова, 36а, Чорнобиль, 07270, Україна
[2] Відокремлений підрозділ «Южно-Українська АЕС» Державного підприємства «НАЕК «Енергоатом», Миколаївська обл., Южноукраїнськ, 55000, Україна

ПОРІВНЯННЯ СТАТИСТИЧНИХ ВЛАСТИВОСТЕЙ ТЕМПЕРАТУРИ ОХОЛОДЖУВАЧА І НЕЙТРОННОГО ПОТОКУ В РЕАКТОРІ ВВЕР-1000

Із використанням вейвлет-аналізу досліджено наявність закономірностей у «шумових» сигналах детекторів нейтронного потоку і температури теплоносія штатної системи внутрішньореакторного контролю реактора ВВЕР-1000. Виконано порівняльний аналіз довгих рядів вимірювань температури теплоносія і щільності потоку нейтронів. В обох параметрах виявлено багатий спектр різноманітних періодичностей. Деякі з них знайдено як у даних температури, так і потоку нейтронів. Проте в динаміці потоку нейтронів і температури виявлено також періодичності, які не корелюють між собою. Показано відмінності між картинами вейвлет-перетворення температур гарячої і холодної ниток: у температурі гарячої нитки виникають додаткові більш високочастотні коливання, які можна приписати розвитку турбулентності. Зроблено висновок, що проаналізовані флуктуації сигналів не є випадковим шумом, а є носіями інформації про стан нейтронної підсистеми реактора. Пропонується виконувати аналіз флуктуацій сигналів штатної системи контролю для діагностики режимів роботи реактора.

Ключові слова: ядерний реактор, нейтрони, теплоносій, статистика.

А. Д. Скорбун[1], С. Н. Стаднык[1], В. Г. Котеленец[2], А. Л. Арванинов[2], А. В. Дробецкий[2]

[1]Институт проблем безопасности АЭС НАН Украины, ул. Кирова, 36а, Чернобиль, 07270, Украина
[2] Обособленное подразделение «Южно-Украинская АЭС» Государственного предприятия «НАЭК «Энергоатом», Николаевская обл., Южноукраинск, 55000, Украина

СРАВНЕНИЕ СТАТИСТИЧЕСКИХ СВОЙСТВ ТЕМПЕРАТУРЫ ОХЛАДИТЕЛЯ И НЕЙТРОННОГО ПОТОКА В РЕАКТОРЕ ВВЭР-1000

С использованием вейвлет-анализа изучено существование закономерностей в «шумовых» сигналах детекторов потока нейтронов и температуры теплоносителя штатной системы внутриреакторного контроля реактора ВВЭР-1000. Выполнен сравнительный анализ длинных рядов измерений температуры теплоносителя и плотности потока нейтронов. В обоих параметрах обнаружен богатый спектр разнообразных периодичностей. Некоторые из них найдены как в температурных данных, так и данных потока нейтронов. Однако в динамике потока нейтронов и температуры обнаружены также периодичности, которые не коррелируют между собой. Показаны отличия между картинами вейвлет-преобразования температур горячей и холодной ниток: в температуре горячей нитки возникают дополнительные более высокочастотные колебания, которые можно приписать развитию турбулентности. Сделан вывод, что проанализированные флуктуации сигналов не являются случайным шумом, а являются носителями информации о состоянии нейтронной подсистемы реактора. Предлагается выполнять анализ флуктуаций сигналов штатной системы внутриреакторного контроля для диагностики режимов работы реактора.

Ключевые слова: ядерный реактор, нейтроны, теплоноситель, статистика.

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