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Study of Parametric Interactions in the Nuclear Reactor Control with Feedback

V. V. Opiatiuk[1)], **I. L. Kozlov**[1)], **V. I. Skalozubov**[1)], **I. A. Ostapenko**[2)]

[1)]Odessa National Technical University (Odessa, Ukraine),
[2)]National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”
(Kyiv, Ukraine)

Abstract. This article considers the principal theoretical possibility of regulating a nuclear power reactor under changing operating modes conditions when external periodic disturbances take place in conditions of changing the operating mode. By the external periodic perturbation a downward change in the conditions of the heat sink was meant. The magnitude of the changes was preliminarily calculated in such a way that the operating conditions of the power plant did not exceed the boundaries of the safe operation zone of the reactor. In the case of approaching the operation parameters to the critical ones, the heat sink was increased until the working conditions returned to their previous state. In this work the amplitude frequency response of a non-linearly enhanced system in the nuclear power plant operating conditions when non-linearly reacting to external periodic influences has been studied. The external cyclic disturbances effect produced on the reactor that initially existed under stationary operating conditions has been considered. The research was carried out by numerical simulation of the competition between processes occurring in a nuclear power plant and determined by the system’s reaction time and relaxation time while responding to periodic external influences. Calculations of the relaxation time dependence on the fixed frequency-revealing external influence’s temperature are presented. Also, the relaxation time dependence on the frequency of external influence at a fixed temperature for systems with various relaxation periods was calculated. It is determined that when the dependence between system temperature and the external influence time is calculated, there exists a wide range of possible frequency control. To evaluate the behavior of a nuclear power reactor under conditions of operating modes changes, a fundamental physical mathematical model of the reactor’s state under external harmonic influence is presented. It is based on the nonlinear Riccati equation. The external harmonic effect was simulated by changing the heat supply and heat removal conditions near the critical point.

Keywords: amplitude frequency response, cyclic disturbances, harmonic effects, reaction time, relaxation time, polycyclic regulation, aperiodic instability

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Адрес для переписки	**Address for correspondence**
Опятюк Владислав Владимирович	Opiatiuk Vladyslav V.
Одесский национальный политехнический университет	Odessa National Technical University
просп. Шевченко, 1,	1, Shevchenko Ave.,
65044, г. Одесса, Украина	65044, Odessa, Ukraine
Тел.: +380 66 772-26-59	Tel.: +380 66 772-26-59
vladopat@ukr.net	vladopat@ukr.net

Исследование параметрических взаимодействий при регулировании ядерного реактора с обратной связью

В. В. Опятюк[1], И. Л. Козлов[1], В. И. Скалозубов[1], И. А. Остапенко[2]

[1]Одесский национальный политехнический университет (Одесса, Украина),
[2]Национальный технический университет Украины «Киевский политехнический институт имени Игоря Сикорского» (Киев, Украина)

Реферат. Рассмотрена принципиальная теоретическая возможность регулирования ядерного энергетического реактора, находящегося под воздействием внешних периодических возмущений, в условиях изменения режимов работы. Под внешним периодическим возмущением подразумевалось изменение условий теплоотвода в сторону уменьшения. Величина изменений предварительно рассчитывалась таким образом, чтобы условия работы энергетической установки не выходили за границы зоны безопасной работы реактора. В случае приближения параметров работы к критическим теплоотвод увеличивался до момента возвращения условий работы в прежнее состояние. Изучен амплитудный частотный отклик нелинейно обостренной системы в условиях работы ядерной энергетической установки, нелинейно реагирующей на внешние периодические воздействия. Рассмотрено воздействие внешних циклических возмущений на реактор, исходно находящийся в стационарном рабочем состоянии. Проведены исследования путем численного моделирования конкуренции процессов, протекающих в ядерной энергетической установке, которые определяются временем реакции и временем релаксации системы на периодическое внешнее воздействие. Представлены расчеты зависимости времени релаксации от температуры внешнего воздействия при фиксированной частоте, времени релаксации от частоты внешнего воздействия при фиксированной температуре для систем с разным временем релаксации. Определено, что при расчете зависимости температуры системы от времени внешнего воздействия существует широкая зона возможного частотного регулирования. Для оценки поведения ядерного энергетического реактора в условиях изменения режимов работы создана принципиальная физико-математическая модель состояния реактора, находящегося под внешним гармоническим воздействием, на основе нелинейного уравнения Риккати. Внешнее гармоническое воздействие моделировалось путем изменения условий теплоподвода и теплоотвода вблизи критической точки.

Ключевые слова: амплитудный частотный отклик, циклические возмущения, гармонические воздействия, время реакции, время релаксации, полицикличное регулирование, апериодическая неустойчивость

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Introduction

At present, the nuclear power plant’ nuclear reactors mainly operate in a stationary operational (basic) mode, when the reactor’ specified power level remains constant for a long time.

Dynamic modes with changes in the reactor power level are associated with transient processes during unit starts and stops, or in cases of emergencies of various types’ [1–4].

Recently, the public and experts in the field of nuclear energy use have been actively discussing the issue of NPP’ nuclear power plants units engagement into daily power control. The ability of nuclear power plants to participate in total energy supply and consumption system load control is a crucial factor in further development of nuclear energy domain [5, 6]. As an example of such general power system load regulation, we can mention France, where more than 75 %

of electricity is produced at nuclear power plants (PWR – type reactors are analogs of WWER ones), and maneuvering modes have been introduced since the mid-70s of the last century. Parameters of maneuvering mode at some French nuclear reactors are shown in Fig. 1 [7].

However, when the reactor operates in transient modes, a complex interweaving of heterogeneous physical processes occurs, which processes form internal feedbacks that cause a destabilizing effect [8].

When these feedbacks are strong enough and changes in the reactor operating parameters reveal proper phase shifts, the reactor's stationary operation mode turns out to be unstable [9–11] and can go to the upper critical state (UCS) zone, which is unacceptable from the point of view of the thermal explosion theory.

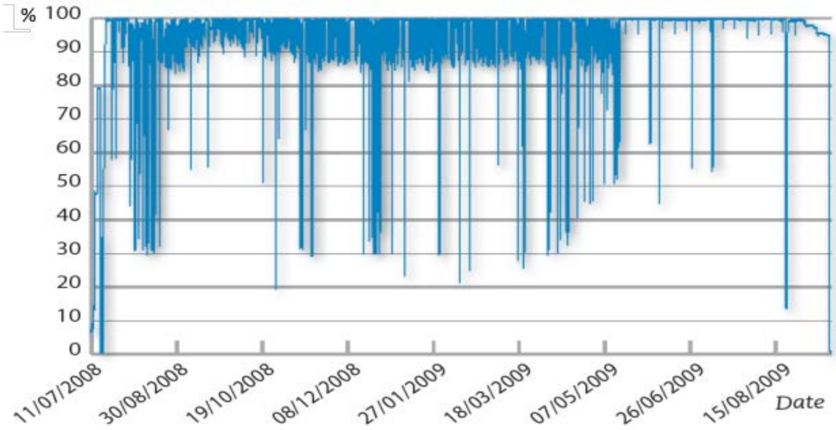

Fig. 1. Power history for a one year from a French PWR (units of 900 MW) in procent of rated power [12] from July, 2008 – August, 2009

The study of transient processes and stability of oscillations in a nonlinear system under parametric excitation allows evaluating its power, amplitude, and frequency characteristics. The analysis of transient processes and stability of oscillations clearly shows the relationship between the initial conditions of impact and the system response in the form of periodic repeated oscillations (polycyclic) [13, 14]. Consideration of transient processes and issues of oscillation stability in nonlinear parametric systems is of considerable scientific and practical interest for creating new methods applied in designing controlled influence modes. This article purpose is to show the principal theoretical possibility of the nuclear reactor polycyclic regulation under changing operating modes conditions through studying the parametric interactions of the system under external harmonic influences.

It is shown in [15–18] that chaotic fluctuations in the neutron density can occur in specific type's nuclear reactors due to the action of internal reactivity feedbacks. In boiling reactors, dynamic chaos can be excited due to feedback on the vapor content in the core [19–21], at reactors with gaseous nuclear fuel due to density feedback [22, 23], and in pulsed batch reactors they are due to the combined action of feedback on the fuel temperature and external periodic changes in reactivity [24].

Theoretical and experimental studies of the nuclear reactors stability show that additional feedbacks due to the presence of regulation and control bodies can also cause unstable operation of the reactor. Steady-state instability can take a variety of forms, the most common of which are aperiodic and oscillatory [25] ones.

Aperiodic instability is characterized by the fact that after small perturbations of the stationary regime, the neutron density and other values characterizing the reactor are monotonically, aperiodically shifting from their stationary values over time.

Oscillatory instability is characterized by self-excitation of increasing fluctuations of the values describing the reactor operation near their stationary values. Due to the nonlinear relationships between these values, oscillations with finite amplitude determined by the reactor parameters (self-oscillations) are established in the reactor.

Main part

To solve the problem of polycyclic regulation for a nuclear reactor under conditions of changing its operating modes, the amplitude frequency response in nonlinear – enhanced systems was studied.

The effect of external periodic disturbances on a reactor initially in a stationary state has been considered. The supposed process is shown in Fig. 2.

In order to adjust the power characteristics, it is assumed to shift the reactor's operating point, for example, to the level of 70 % of the design capacity and periodically produce effects to the reactor by changing the heat exchange conditions. Reducing the frequency of exposure will lead to a decrease in the released power of the operating reactor.

Higher frequency exposure will lead to increased power during reactor operation [26]. In this case, the main condition shall be to prevent the reactor from operating at mode close to the UCS.

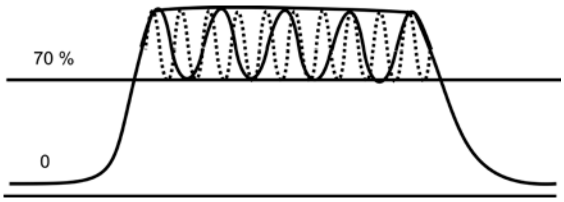

Fig. 2. Supposed process of the nuclear reactor operation under polycyclic control

This process is described by the following Riccati equation [27, 28]:

$$\frac{d\theta}{d\tau} = \kappa e^{\theta} - \theta + \theta_A \cos\omega'\tau, \tag{1}$$

where θ – dimensionless temperature parameter; $\tau = t/\tau_\gamma$ – dimensionless exposure time; $\kappa = \tau_r/\tau_x$ – Semyonov parameter; ω' – dimensionless frequency; θ_A – amplitude of external harmonic influence in dimensionless form

$$\theta_A = T_A E \big/ R T_\infty^2 , \tag{2}$$

where T_A – temperature in the reactor, K; T_∞ – temperature of the cooling medium, K; E – activation energy (5.75 MeV); R – universal gas constant [29].

The dimensionless frequency in its physical sense is the ratio of two characteristic times of the process: the relaxation time and the period of disturbance action.

There is no analytical solution to equation (1), since the right-hand side contains a source written in harmonic form. Therefore, the numerical parametric calculation of this equation solution that includes the temperature parameter variation with the amplitude of the external harmonic action θ_A and the perturbation frequency ω' is carried out.

Also, the research was carried out by computer calculations of the competition between processes that are determined by the system's reaction time and relaxation time against the periodic external influence.

The calculation of the system temperature amplitude parameter dependence on the external influence time [30] is shown in Fig. 3, where it can be seen that there exists a wide range of possible frequency control.

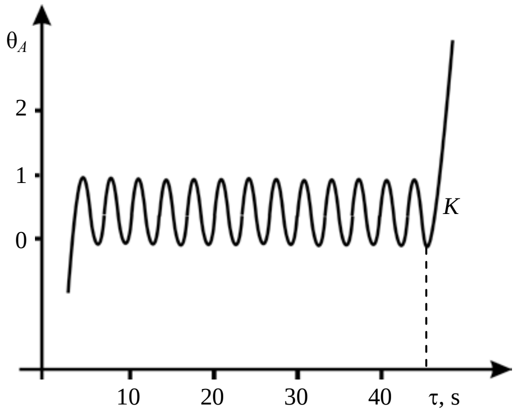

Fig. 3. Graph of the dependence between the θ_A amplitude temperature parameter and the time τ of enhanced system under the influence of external factors

The K zone shown in the right part of the graph represents an intolerable mode of reactor operation. In the future, for each set of parameters, the induction time τ_i was found, which means the duration of nonlinear critically enhanced system transition from a stable initial state to an unstable explosive one.

Interpretation of the results and their approbation

Fig. 4, 5 show the results of the induction time τ_i dependence on the temperature parameter of amplitude θ_A and the external influence frequency ω, respectively. The Fig. 4 shows the descending dependence of the induction time on the temperature perturbation amplitude at various fixed frequencies. This result is obvious, since for a nonlinear system of an exothermically reacting medium, its response to the heating phase is stronger than the response of the system cooling phase. The Fig. 5 shows an increase in the induction time with increasing frequency when the external perturbation amplitude temperature parameter is fixed. This is due to the fact that, with increasing frequency, the response of a nonlinear system to external influences decreases due to its thermal inertia.

Thus, the induction time is a function of the amplitude temperature parameter and exposure frequency $\tau_i = f\left(\theta_A,\, \omega'\right)$. When this transition time is fixed, the amplitude temperature parameter depends on the frequency. This relationship is shown in Fig. 6 for different transition times. It can be seen with high accuracy (~1 %) that curves 1–3 are approximated by a linear function.

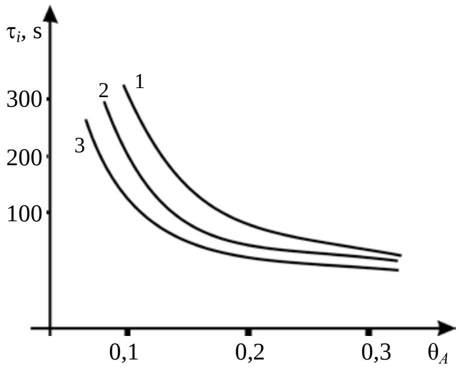

Fig. 4. Graph of the τ_i induction time dependence on the external influence amplitude θ_A at a fixed frequency: 1 – pulsation period of 1000 s; 2 – 2000 s; 3 – 3000 s

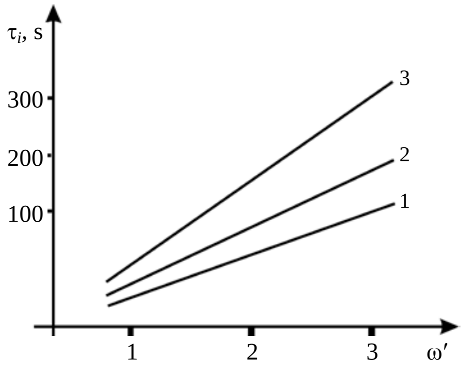

Fig. 5. Graph of the τ_i induction time dependence on the external influence frequency $\omega' = \omega\tau_\gamma$ at a fixed temperature: 1– 500 K; 2 – 700 K; 3 – 900 K

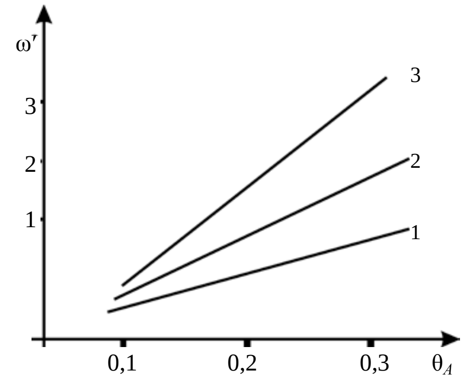

Fig. 6. Graph of the $\omega' = \omega\tau_\gamma$ external influence frequency dependence on the θ_A external influence amplitude for an enhanced system, in which the transition from a low-temperature to a high-temperature state was observed for a fixed time: 1 – 3000 s; 2 – 2000 s; 3 – 1000 s

So, in order for the transition of an enhanced system from one state to another, a higher frequency requires more energy, since the temperature is proportional to the thermal energy. That is, the external influence energy, which is sufficient to transfer the system from one stable state to another, is proportional to the impact frequency. This result echoes the well-known quantum-mechanical relation [31, 32], where, just as in our case, the energy is proportional to the frequency in the first power.

The considered solution to the polycyclic reactor power control problem is possible only after the development of new general recommendations for the technological regulations and technical conditions of reactor operation, operation of control and measuring equipment and safety systems for such a nuclear reactor control conditions.

CONCLUSIONS

1. The principal possibility of polycyclic control for a nuclear reactor under conditions of operating modes changing through investigation into the system parametric interactions under external harmonic influences has been considered.
2. The relations for studying the stability of a nonlinear system oscillations in parametric excitation zones have been described.
3. It is determined that the response of a non-linearly reacting system is directly proportional to the frequency and amplitude of the harmonic effect.
4. The results of study on the assessing the induction time dependence from amplitude temperature parameter and frequency of external impact, respectively, have been presented.
5. The necessity of new recommendations development and elaboration of algorithms for the technological regulations and technical conditions of a nuclear reactor operation in conditions of polycyclic control has been outlined.

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