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A system of automated power control during disturbances that occur inside a PWR nuclear reactor

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Abstract: In order to increase the service life of NPPs is proposed to change the power of the nuclear reactor depending on the needs of consumers. However, power maneuvering increases the risk of an emergency situation, since it is very difficult to maintain a steady state of the reactor when moving from one power level to another. For this, it is necessary to adapt the methods of operational control when changing the power of a nuclear reactor. An approximation model is proposed, with the help of which it is possible to improve the system of automated power control in case of internal disturbances of a nuclear reactor. The change in reactivity that occurs as a result of a change in the concentration of xenon when maneuvering the power of a nuclear power plant was attributed to internal disturbances. An approximation model of the processes was built using the Padé approximation.

Keywords: Approximation model, automated control system, xenon oscillations, polynomial, Padé approximation.

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1. Introduction

Recently, most of the countries of the European Union are switching to "green energy", but a significant percentage of electricity imports from third countries of the world is observed. Which shows the inability to satisfy the needs of all consumers within the framework of "green energy". In this regard, the operation of the nuclear power plant still remains important and significant, as it allows generating a significant amount of energy to stabilize the operation of the power system. One of the features of NPP operation is the duration of the reactor power control process. The use of the power of a nuclear reactor in the conditions of dispatching electricity flows and the possibility of increasing the operation of the NPP attracts many investors. In this regard, it is necessary to pay attention to the methods of operational management of changes in reactor power.

2. Object and subject of research

The object of the research is the system of automated control of PWR in case of internal disturbances of the active zone. The subject of the study is the methods of the automated control system, which restrain internal disturbances inside the PWR reactor during maneuvering of its power.

3. Target of research

The purpose of this study is to improve the system of automated control of energy release, which changes as a result of internal disturbances inside the active zone of the reactor, at the expense of the approximation model.

To achieve the goal, it is necessary to: implement an approximation model using an approximation polynomial and approximations. It is necessary to design a control method on the basis of which it is possible to create an automated control system that will help restrain xenon oscillations and maintain the axial offset (quantitative measure of reactor stability).

4. Literature analysis

Most nuclear power plants operate only in stationary mode at maximum power. The power control systems used in the operation of a nuclear reactor are not capable of independently making the transition from one power level to another. It is the transition of the stationary state of the reactor from one power level to another that is carried out with the help of an operator who receives data and manually controls the reactor [1-2]. The capability of the computing equipment is very high and allows to measure the necessary technological parameters very quickly, but it is not capable of performing calculations (of neutron-physical parameters) in real time when the reactor is moving from one level to another [3, 10]. Regardless of the method of power regulation, a nuclear reactor is constantly affected by external and internal disturbances [15]. Special attention is paid to the change in reactivity that occurs as a result of xenon oscillations [12-13]. Computing equipment that calculates parameters for the operation of a nuclear reactor is not capable of working in real time. The basic model that describes the processes inside a nuclear reactor contains a complete system of differential equations and their solutions [4]. To solve such a problem, you can use an approximation model, which is built on the basis of the results of calculations of the main model [5, 11]. In the proposed model, the calculation results coincide (have a small deviation) with the calculation results of the main model for a certain period of time [6-7]. The approximation model can be used for the automated control system of the reactor during power maneuvering [8].

5. Research methods

Disturbances that occur during the operation of a nuclear reactor are regulated by the operator, who receives information from the sensors and then adjusts the regulators [9, 14]. Several steps were taken to create an approximation model. First, approximation polynomials were obtained, the degree of which was chosen to the appropriate accuracy. The corresponding approximation error for the highest (tenth) power was 3.6%. After the approximation of the two-dimensional data, we will obtain the calculated coefficients of the approximation polynomials when the reactivity changes as a result of increasing the reactor power (Fig. 1), which are given in Table 1.

Table 1. Estimated approximation coefficients in the change in reactivity in the case of an increase in reactor power

Coefficients of polynomials	Graph No (Fig.1)			
	1	2	3	4
c_{10}	–5.696E+04	–5.137E+04	–4.269E+04	7.805E+04
c_9	2.254E+05	2.254E+05	2.024E+05	–2.391E+05
c_8	–3.867E+05	–4.240E+05	–4.088E+05	2.748E+05
c_7	3.773E+05	4.473E+05	4.585E+05	–1.255E+05
c_6	–2.307E+05	–2.909E+05	–3.123E+05	–1.108E+04
c_5	9.169E+04	1.210E+05	1.330E+05	3.585E+04
c_4	–2.365E+04	–3.240E+04	–3.524E+04	–1.536E+04
c_3	3.757E+03	5.472E+03	5.643E+03	3.010E+03
c_2	–2.921E+02	–5.381E+02	–5.115E+02	–2.858E+02
c_1	–7.093E+00	1.963E+01	1.982E+01	1.095E+01

When calculating the coefficients of the polynomial, the magnitude of the change in power was reduced by three orders of magnitude, and applying the Laplace transformation, we obtain:

$$\begin{gathered}\rho_j = a\cdot\left(\Delta P_j\cdot 10^{-3}\right)^4 + b\cdot\left(\Delta P_j\cdot 10^{-3}\right)^3 + \\ + c\cdot\left(\Delta P_j\cdot 10^{-3}\right)^2 + d\cdot\left(\Delta P_j\cdot 10^{-3}\right),\end{gathered} \tag{1}$$

Where the coefficients a, b, c, d have the following values:

$$\begin{aligned} a &= -0.5267\cdot f_4 + 0.7901\cdot f_3 - 0.5267\cdot f_2 + 0.1317\cdot f_1, \\ b &= +3.5556\cdot f_4 - 4.7407\cdot f_3 + 2.7654\cdot f_2 - 0.5930\cdot f_1, \\ c &= -7.7037\cdot f_4 + 8.4444\cdot f_3 - 4.1481\cdot f_2 + 0.8148\cdot f_1, \\ d &= +5.3333\cdot f_4 - 4.0000\cdot f_3 + 1.7778\cdot f_2 - 0.3330\cdot f_1. \end{aligned} \tag{2}$$

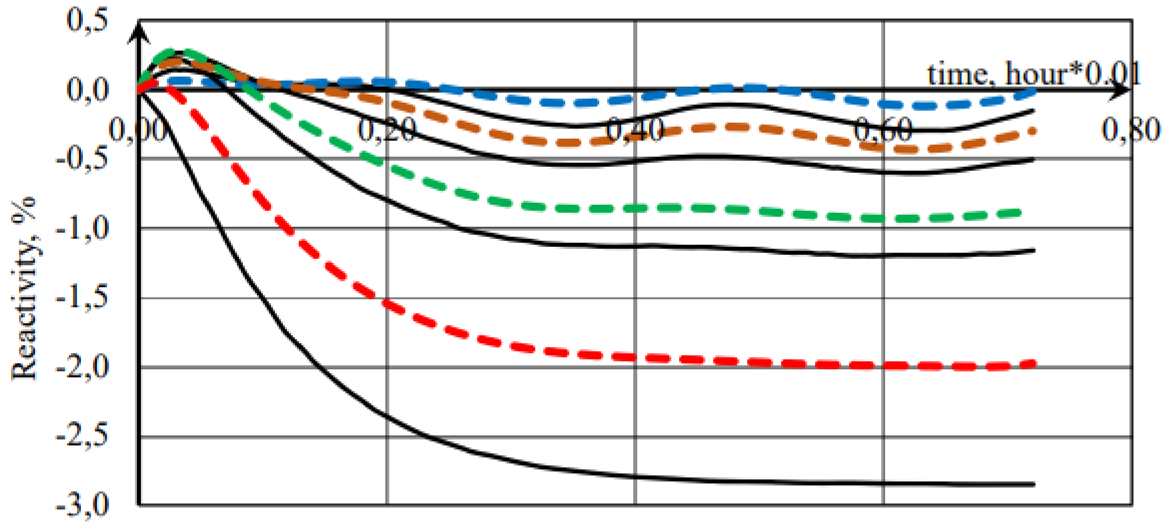

Fig. 1. Change in reactivity when power is increased to 3000 MW.

In fig. 1. The change in reactivity when the reactor power is increased from 0 to 3000 MW is presented, where the graphs corresponding to the change in reactivity due to the increase in reactor power are shown in black, and the dotted lines are indicated that correspond to a certain load (blue -

300 MW, brown - 1100 MW, green – 2000 MW, red – 2700 MW). Taking into account the mapping of the numerical solution in the space of mappings, which is represented by approximation, we obtain the following expression

$$L\left\{\sum_{i=1}^{n} c_{i\,j} t^{i}\right\} = \\ = \left(\frac{1}{p}\right)^{2} \cdot \frac{b_4 p + b_3 p^2 + b_2 p^3 + b_1 p^4 + b_0 p^5}{a_5 + a_4 p + a_3 p^2 + a_2 p^3 + a_1 p^4 + p^5}. \tag{3}$$

Where the coefficients *bi*, *ai* from (3) are presented in Table 2

Table 2. Estimated coefficients and roots of the Pade approximation in the case of an increase in reactor power

№	graph 1		graph 2		graph 3		graph 4	
	a_i	b_i	a_i	b_i	a_i	b_i	a_i	b_i
5	3.65e+6	–	1.36e+6	–	8.77e+5	–	4.12e+5	–
4	6.66e+5	–9.94e+6	2.69e+5	–1.30e+6	1.83e+5	–1.20e+5	9.86e+4	2.71e+5
3	5.70e+4	–7.63e+5	2.60e+4	–8.08e+4	1.90e+4	–5.05e+4	1.07e+4	–5.96e+4
2	2.85e+3	–4.63e+4	1.53e+3	2.70e+3	1.23e+3	7.62e+3	7.72e+2	6.47e+3
1	8.32e+1	–1.17e+3	5.60e+1	2.26e+1	4.94e+1	–4.41e+1	3.51e+1	–1.88e+2
0	–	–7.09e+0	–	1.96e+1	–	1.98e+1	–	1.09e+1
root								
p_1	–35.444		–17.059		–15.343		–9.065	
p_2	–15.669–6.659*i*		–14.017–8.840*i*		–12.553–8.842*i*		–10.378–9.324*i*	
p_3	–15.669+6.659*i*		–14.017+8.840*i*		–12.553+8.842*i*		–10.378+9.324*i*	
p_4	–8.209–16.963*i*		–5.443–16.143*i*		–4.473–14.918		–2.618–15.052*i*	
p_5	–8.209+16.963*i*		–5.443+16.143*i*		–4.473+14.918		–2.618+15.052*i*	

Comparison of calculations using the approximation polynomial and the Padé approximation are presented in Fig. 2. Adequacy of computational solutions performed using approximation was also verified.

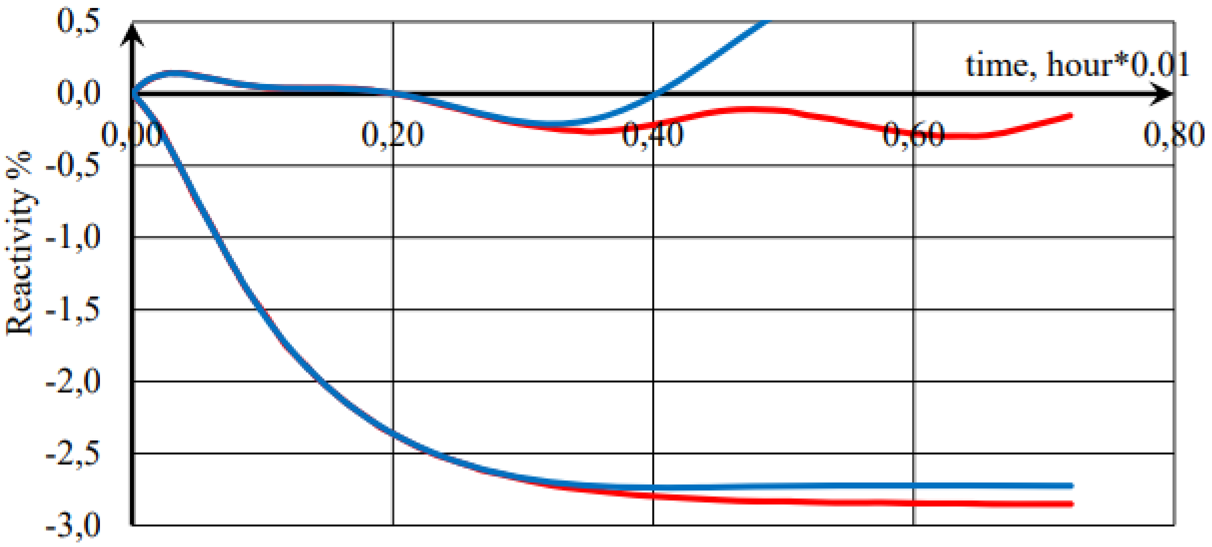

Fig. 2. Comparison of calculated solutions of the approximation polynomial (red line) and the Padé approximation (blue line) when the power is increased to 3000 MW.

Fig. 2 presents graphs comparing the approximation polynomial (red line) and the Padé approximation (blue line), which show that at the 30 hour mark (0.30 in Fig. 2) the two graphs coincide, which indicates their interchangeability.

In the same way, the coefficients of the approximation polynomial were calculated when the reactivity changes in the resulting decrease in the reactor power. The coefficients of the approximation polynomial are presented in Table 3.

Table 3. Estimated approximation coefficients in the change in reactivity in the case of a reduction in reactor power

Coefficients of polynomials	Graph No (Fig.3)			
	1	2	3	4
c_{10}	7.61E+03	–9.52E+03	–4.28E+06	–1.68E+05
c_9	–2.96E+04	5.91E+03	1.07E+07	6.27E+05
c_8	5.12E+04	4.94E+04	–1.11E+07	–9.76E+05
c_7	–5.32E+04	–1.12E+05	6.23E+06	8.18E+05
c_6	3.83E+04	1.12E+05	–2.00E+06	–3.95E+05
c_5	–2.09E+04	–6.35E+04	3.56E+05	1.08E+05
c_4	8.93E+03	2.22E+04	–2.62E+04	–1.46E+04
c_3	–2.86E+03	–4.78E+03	–1.35E+03	4.68E+02
c_2	5.97E+02	6.06E+02	3.71E+02	8.13E+01
c_1	–5.41E+01	–3.49E+01	–1.99E+01	1.10E+01

In the case of reducing the power of the reactor, the coefficients of the polynomial were also calculated, where the magnitude of the change in power was reduced by three orders of magnitude and the Laplace transformation was applied and similar (2) values of the coefficients *a*, *b*, *c*, *d* were obtained.

Taking into account the mapping of the numerical solution in the mapping space, which is represented by the approximation (3), the coefficients bi, ai and the roots of (3) are presented in Table 4.

Table 4. Estimated coefficients and roots of the Pade approximation in the case of a reduction in reactor power

№ coefficient	graph 1		graph 2		graph 3		graph 4	
	a_i	b_i	a_i	b_i	a_i	b_i	a_i	b_i
5	1.61E+5	–	9.91E+5	–	1.41E+7	–	2.08E+6	–
4	6.72E+4	5.18E+5	2.18E+5	7.06E+5	1.56E+6	1.21E+6	3.29E+5	6.95E+5
3	9.94E+3	–4.4E+4	2.29E+4	–1.1E+5	9.10E+4	–5.9E+5	2.79E+4	–1.2E+5
2	7.70E+0	–1.4E+4	1.45E+3	–1.1E+4	3.38E+3	–1.6E+4	1.54E+3	2.11E+3
1	3.73E+1	–8.2E+2	5.60E+1	–7.4E+2	8.04E+1	–8.6E+2	5.44E+1	–1.8E+2
0	–	–5.4E+1	–	–3.5E+1	–	–2.0E+1	–	–6.2E+0
roots								
p_1	–4.770		–18.144		–28.140		–18.983	
p_2	–11.158–3.007*i*		–13.306–6.878*i*		–20.076–17.042*i*		–14.161–11.871*i*	
p_3	–11.158+3.007*i*		–13.306+6.878*i*		–20.076+17.042*i*		–14.161+11.871*i*	
p_4	–5.110–15.059*i*		–5.631–14.548*i*		–6.068–26.205*i*		–3.565–17.566*i*	
p_5	–5.110+15.059*i*		–5.631+14.548*i*		–6.068+26.205*i*		–3.565+17.566*i*	

Comparison of calculations using the approximation polynomial and the Padé approximation are presented in Fig. 3. Adequacy of computational solutions performed using approximation was also verified.

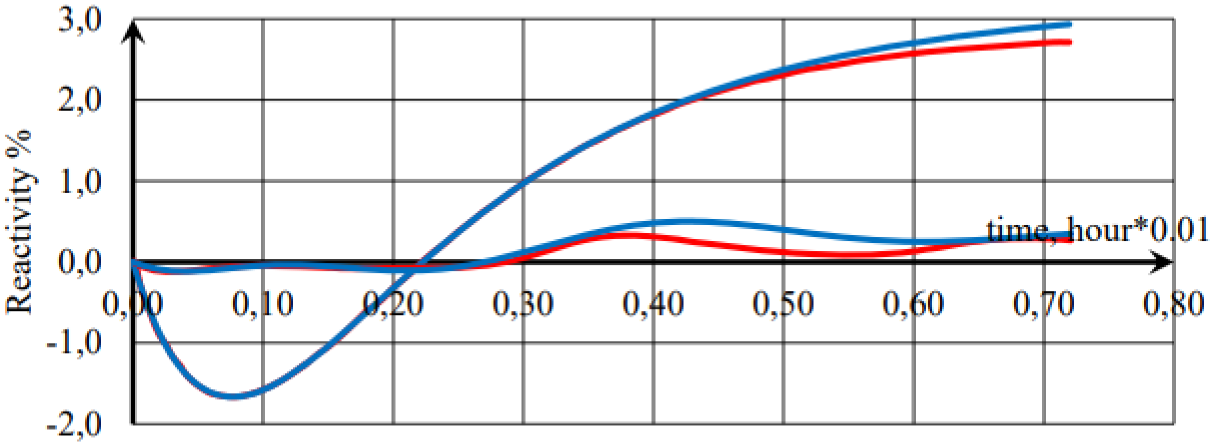

Fig. 3. Comparison of the computed solutions of the approximation polynomial (red line) and the Padé approximation (blue line) at reduced power.

Fig. 3 shows graphs comparing the approximation polynomial (red line) and the Padé approximation (blue line), which show that at the 30 hour mark (0.30 in Fig. 3) the two graphs coincide, as well as in the case of increasing power, which indicates their interchangeability. The conducted analysis of the behavior of the reactor in the maneuvering mode for 7 days (one week) is presented in fig. 4-5.

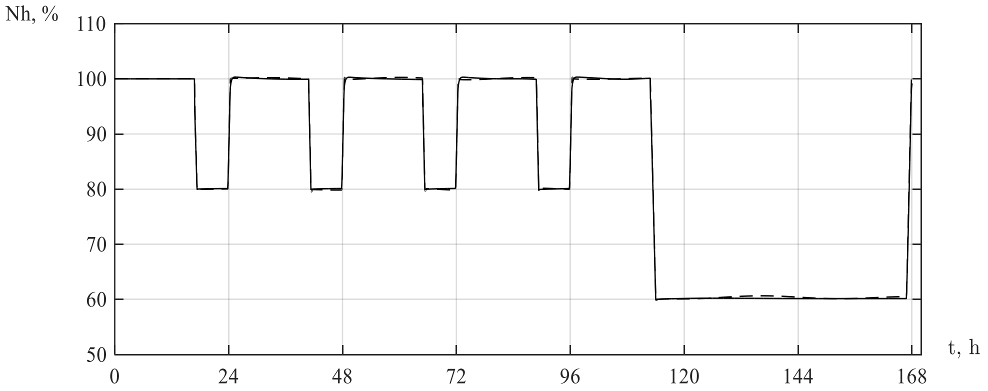

Fig. 4. Change in the thermal power of the nuclear reactor during 7 days of loading.

Fig. 4 shows the power change behavior: on working days, the maximum power was used during the day, which was 100%, at night, the power was reduced to 80%, and on weekends, it was reduced to 60%. The dashed line shows the graphs when the maneuver is carried out with the help of the classic control system, and the solid line shows the power maneuver with the help of the improved control system (using the approximation model). An enlarged scale of behavior of the thermal power of the reactor during maneuvering mode for 7 days is presented in Fig. 5, where we see small deviations (0.2%) of the power of the nuclear reactor when using the classical control system (mark-1) and the modernized control system (mark -2).

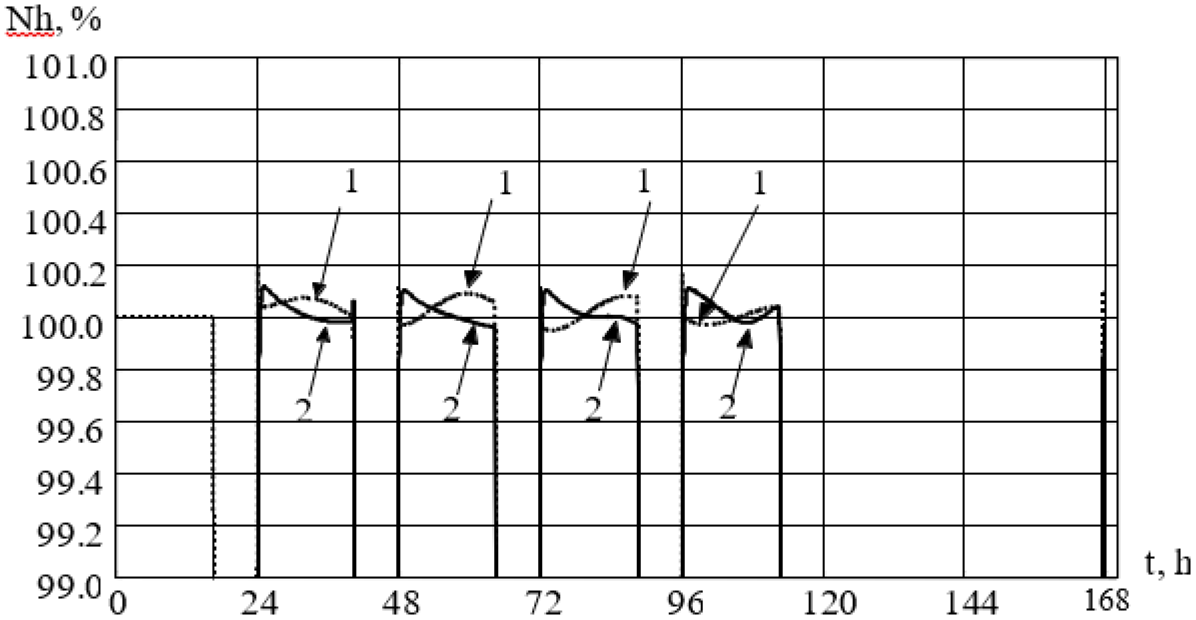

Fig. 5. The change in thermal power of the nuclear reactor during 7 days of loading is shown on an enlarged scale.

6. Research results

The results of calculations of two models in case of increase and decrease of load are used as initial data. The results obtained on the basis of the improved model coincide with the results obtained on the basis of the classical nonlinear physico-mathematical model for a certain period of time, which allows to create an automated control system to compensate for the reactivity caused by xenon oscillations. Checking the adequacy of the improved model expediently reflects the processes that take place in the management object. The solutions obtained in the case of load increase and decrease indicate their compliance in a time interval of approximately 24 hours. This time is enough to compensate for the first half-life of xenon oscillations. This allows to pre-calculate the parameters needed to adjust the power regulator when increasing or decreasing power for each process based on the obtained transfer functions of the approximation models. Then, when the power of the nuclear reactor and the elapsed effective day change, adjust the power regulator according to the new properties of the control object. However, the developed method requires early calculation of the approximation model using the results of neutron-physical calculations of nuclear power equipment and subsequent calculation of regulator settings.

7. Prospects for further research development

The use of a modernized control system will allow changing the power of the nuclear reactor depending on the needs of the power system without increasing the risk of an emergency situation with frequent loading of the nuclear reactor.

8. Conclusions

An approximation model of the processes was built using the Padé approximation. The developed automated control system based on the approximation model will allow to correct the change in the power of the nuclear reactor, with the change in reactivity caused by xenon fluctuations. The solutions obtained in the case of load increase and decrease indicate their compliance in a time interval of approximately 24 hours. When the power of the nuclear reactor changes (taking into account the past effective day), the power regulator is reset according to the new calculations. When the power of the nuclear reactor changes (taking into account the past effective day), the power regulator is reset according to the new calculations.

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