DOI: https://doi.org/10.15276/hait.06.2023.9
UDC 621.039.56:681.5

A method for searching the best static program for nuclear power unit control in the event of perturbations of different nature

Konstantin V. Beglov[1)]
ORCID: https://orcid.org/0000-0002-5277-2577; beglovkv@gmail.com
Yevhenia O. Odrekhovska[2)]
ORCID: https://orcid.org/0000-0003-3134-4204; jenia1991@i.ua
Taia V. Petik[1)]
ORCID: https://orcid.org/0009-0001-8817-1706; taiapetik@gmail.com
Viktoriia V. Vataman[1)]
ORCID: https://orcid.org/0000-0003-4403-5814; vataman043@gmail.com
[1)] Odessa Polytechnic National University, 1, Shevchenko Av. Odessa, 65044, Ukraine
[2)] Separate unit “Pivdennoukrainska NPP”, Industrial Site, Yuzhnoukrainsk, Mykolaiv Region, 55000, Ukraine

ABSTRACT

Considering the current state of Ukraine's energy sector in a dangerous and unstable environment, the operation of nuclear power plants is one of the most important sources of electricity supply for the state. The development of the theory of optimal control and the technical level of automated process control systems in the current state of affairs make it possible not to reduce the efficiency of controlling a nuclear power unit, not only by changing the parameters at any load, but also by changing the structure of automation equipment capable of implementing a certain static control program of power, which currently eliminates the influence of internal and external disturbances, without reducing safety indicators. The article considers the situation when the linear programming method is not applicable for solving the control problem. In this case, the decision at each stage does not depend on the decision at the previous one. This is where target programming comes in handy – this is one of the methods of multi-criteria optimization, in the theory of which decision-making problems are solved simultaneously according to several criteria. The purpose of the work is to ensure the safe and efficient operation of a nuclear power unit in an energy system that is not constant in operational states. Using a mathematical model of a nuclear power unit, experiments were carried out to simulate the switching of control programs. The simulation model of the automated power control system, based on the bumpless switching of static programs according to the technological methods of operating power equipment, made it possible to form a change in the current model of the control program, as well as eliminate the static control error and get the response of process dependent parameters to program switching. Also, based on the results of the research, an objective function was proposed, which includes three normalized criteria with different objectives. In particular, the problem of optimizing the switching of static power control programs was solved by minimizing the objective function, which combines such characteristics as the efficiency and safety of the operation of a nuclear power unit.

Keywords: Nuclear reactor; control system; power regulation; safety indicators; fuel cycle; static programs

***For citation*: Beglov K. V., Odrekhovska Y. O., Petik T. V., Vataman V. V. “A method for searching the best static program for nuclear power unit control in the event of perturbations of different nature”. *Herald of Advanced Information Technology.* 2023; Vol.6 No.2: 139–151. DOI: https://doi.org/10.15276/hait.06.2023.9**

INTRODUCTION

Given the state of Ukraine's energy sector in dangerous military conditions, the operation of nuclear power plants (NPPs) remains one of the important means of providing the state with electricity. When a nuclear power unit is operated in a steady-state, it is affected by many internal perturbations. The number of external disturbances increases when the nuclear power unit is operated in the mode of a daily load cycle in wartime, which leads to a change in the values of process dependent parameters.

Modern automated process control systems for nuclear power plants allow not only to perform control tasks using a static power control program based on the feedback principle, but also, using the accumulated information about the state of the equipment, to predict the possible states of a nuclear power unit, taking into account disturbances of various nature, including during unscheduled unloading of a nuclear power unit during destruction of the power grid. The development of the theory of optimal control and the technical level of automated process control systems, in the current state of affairs, make it possible not to reduce the efficiency of control of nuclear power unit, not only by changing the parameters at any load, but also by changing the structure of automation hardware capable of implementing one or another static power control program that currently neutralize the impact of internal and external disturbances, without reducing safety performance.

ANALYSIS OF THE ISSUE

It is known that linear programming is a mathematical apparatus developed for solving optimal problems with linear expressions for the optimality criterion and linear constraints on the range of variables. To solve a large range of linear programming problems, there is an almost universal algorithm – the simplex method, which allows finding the optimal solution for the vast majority of problems in a finite number of iterations. The type of restrictions used (equality or inequality) does not affect the possibility of applying the specified algorithm. Additional optimality checks for the resulting solutions are not required [1].

The task of switching belongs to the class of discrete systems because the switching of control programs will supposedly be carried out only at a given moment of power of a nuclear power unit. The control programs do not switch on the way of reducing or increasing power. Therefore, the linear programming method is not applicable for solving the problem, which is additionally confirmed in [2].

The dynamic programming approach is to solve each subproblem only once, using the same number of calculations. This is especially useful in cases where the number of repeating subtasks is exponentially large.

The considered problem is similar to the transport problem. But in such a problem, each successive solution depends on the previous solution. In our case, the solution at each stage does not depend on the solution at the previous one. The decision to decrease/increase the power of the nuclear power unit according to a certain control program does not depend on previous decisions [3].

It should be noted that in dynamic programming the sum of local optimal solutions does not necessarily lead to a global optimal solution [4].

Target programming is one of the methods of multicriteria optimization (MCO), in the theory of which decision-making problems are solved simultaneously by several criteria [5].

The MCO problem is posed as follows: it is necessary to find the numbers $x_1, x_2, \ldots, x_n$ that satisfy the system of constraints:

$$g_i(x_1, x_2, \ldots, x_n) \le b_i,\ i = 1,2,\ldots,m, \qquad (1)$$

for which the functions are:

$$z_k = f_k(x_1, x_2, \ldots, x_n),\ k = 1,2,\ldots,K, \qquad (2)$$

reach their maximum value.

A large number of points $X = (x_1, x_2, \ldots, x_n)$, satisfying system (1) form an accessible region $D \subset R^n$. The elements of the set D are called admissible solutions or alternatives, and the numerical functions $f_k,\ k = 1,2,\ldots,K$ are called objective functions or criteria defined on the set D. In the formulation of task (1) – (2) there are K objective functions. These functions reflect the set $D \subset R^n$ into the set $F \subset R^K$, which is called the set of attainability.

The name of this method is due to the fact that the person who makes the decision sets certain goals $\bar{f}_1, \bar{f}_2, \ldots, \bar{f}_K$ for each criterion.

The MCO problem in this case turns into the problem of minimizing the sum of deviations with some indicator p:

$$z = \left(\sum_{k=1}^{K} w_k \left|f_k(X) - \bar{f}_k\right|^p\right)^{\frac{1}{p}} \rightarrow min, \text{ at } X \in D, \qquad (3)$$

where w_k – some weighting coefficients that characterize the importance of a particular criterion.

Task (3) can be specified depending on the values of the parameter p and the given objectives.

In particular, for $p = 2$ and $w_k = 1$ we get the problem of minimizing the sum of squared deviations:

$$z = \sqrt{\sum_{k=1}^{K} \left|f_k(X) - f_k^*\right|^2} \rightarrow min \text{ at } X \in D,$$

in which the Euclidean distance from the reachable set F to the "absolute maximum" $f^* = (f_1^*, f_2^*, \ldots, f_l^*)$ is minimized in the criteria space. Here $f_k^* = \max_{X \in D} f_k(X)$.

Complications caused by the incommensurability of the values $|f_k(X) - f_k^*|$, can be overcome by normalizing the criteria, considering the following optimization problem:

$$z = \sqrt{\sum_{k=1}^{K} \left(\frac{\left|f_k(X) - f_k^*\right|}{f_k^*}\right)^2} \rightarrow min \text{ at } X \in D. \qquad (4)$$

The criteria of the objective function are defined, the objectives of each of the criteria are given, and minimizing the distance from the set of attainability to the "absolute maximum" in the space of criteria will give the optimal solution. At this stage of solving the problem, the weighting coefficients of each of the criteria are equal to one. In the future, the simulation results will show whether it is necessary to change the value of these coefficients or not [6].

THE PURPOSE OF THE ARTICLE

The aim of the work is to provide the operation of nuclear power units in a power system that is not constant in terms of operational states by searching for the best method for switching static control programs when disturbances of various nature are applied.

To achieve the goal, the following tasks must be solved:

– study the change in technological indicators in transient modes when choosing a static control program for nuclear power unit;

– substantiate the criteria and objective function of finding the best solution for the process of switching static power control programs;

– develop a method for switching static power control programs by searching for the best control program depending on disturbances and the current state of power equipment.

MAIN PART. ANALYSIS OF CHANGES IN PROCESS DEPENDENT PARAMETERS IN TRANSIENT MODES FOR STATIC PROGRAMS OF CONTROL OF A NUCLEAR POWER UNIT

Using the mathematical model of a nuclear power plant with a pressurized water reactor, implemented on the basis of Matlab Simulink [5], experiments were carried out to simulate the switching of control programs. A total of 6 switching's made, namely from T_{av}=const to T_{in}=const; from T_{in}=const to T_{av}=const; from T_{av}=const to P_2=const; from P_2 =const to T_{av}=const; from T_{in}=const to P_2=const; from P_2=const to T_{in} = const. The experiment was carried out as follows: the reactor power was reduced to 80% when operating according to one control program, and reaching 100 % power was carried out according to another.

In Fig. 1, Fig. 2 and Fig. 3, points 1 and 2, corresponding to zero power, indicate the absence of a temperature difference at the inlet and outlet of the reactor core. Consequently, with an increase in the power of the nuclear power unit, a temperature difference arises at the inlet and outlet of the core, which is shown in the figures mentioned above. Vertical lines located at the power level of 80 % indicate transitions from one control program to another when they are switched. In Fig. 1 Fig. 2 and Fig. 3, from points 1 and 2, the temperatures of the coolant at the outlet, average and at the inlet to the reactor core go from top to bottom. Black color shows how the coolant temperature changes according to the static program T_{av}=const. The red color shows how the coolant temperature changes according to the static program T_{in}=const. The blue color shows how the coolant temperature changes according to the static program P_2=const.

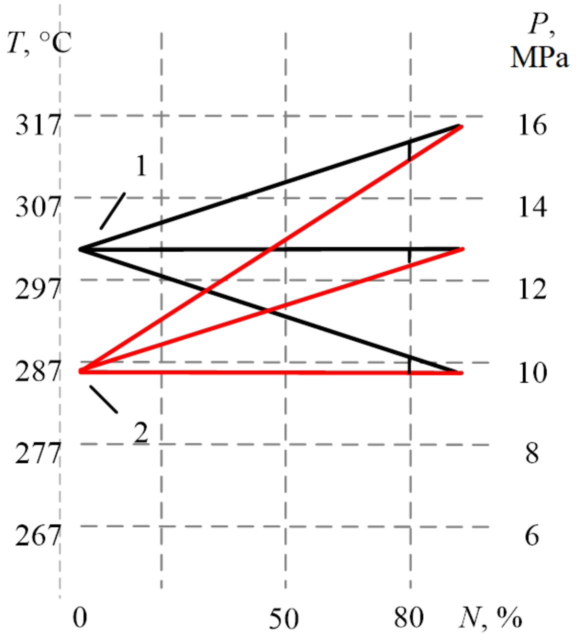

Fig. 1. **Characteristics of a nuclear power unit with a pressurized water reactor when switching T_{av}=const and T_{in}=const**
Source: **compiled by the authors**

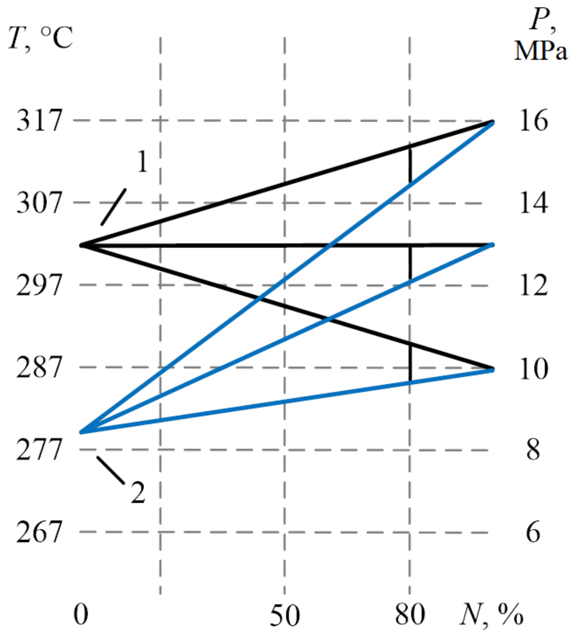

Fig. 2. **Characteristics of a nuclear power unit with a pressurized water reactor when switching T_{av}=const and P_2=const**
Source: **compiled by the authors**

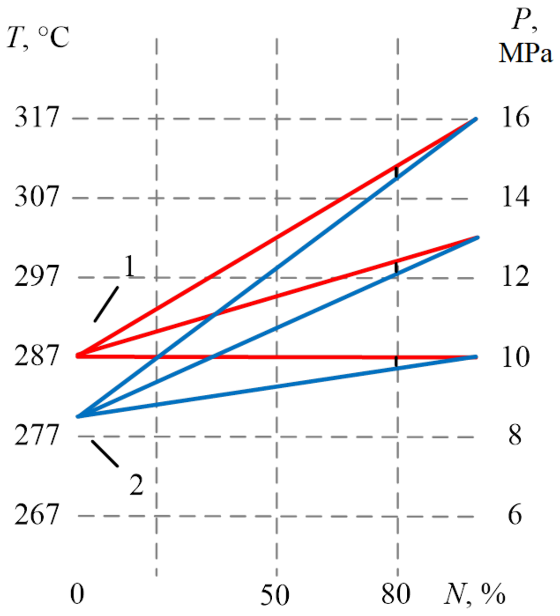

Fig. 3. **Characteristics of a nuclear power unit with a pressurized water reactor when switching T_{in}=const and P_2=const**
Source: **compiled by the authors**

Table 1 shows the value of the temperature deviation at the time of switching control programs at 80 % of the power of the nuclear power unit, which was obtained using the optimization conditions shown in Fig. 1 of [7].

Table 1. **Values of temperature deviations at the moment of program switching**

Switching control programs	ΔT_{in}, °C	ΔT_{av}, °C	ΔT_{out}, °C
From T_{av}=const to T_{in}=const	2.4	2.1	2
From T_{in}=const to T_{av}=const	- 2.4	-2.1	-1.8
From T_{av}=const to P_2=const	4.1	3.5	3.1
From P_2=const to T_{av}=const	- 4	- 3.5	- 3.2
From T_{in}=const to P_2=const	1.6	1.5	1.5
From P_2=const to T_{in}=const	- 1.6	- 1.5	- 1.2

Source: **compiled by the authors**

CRITERIA AND OBJECTIVE FUNCTION FOR SEARCHING THE BEST SOLUTION FOR THE PROCESS OF SWITCHING STATIC CONTROL PROGRAMS

The conditions of the problem are as follows: consider a 4-year campaign of a reactor plant operated under a certain power control program.

The reactor plant will routinely reduce power in the evening, operating according to the selected control program, and in the morning, ascending power will be carried out according to another (one of three) control programs. Thus, the static power control program can be changed in the evening. Everything will depend on the decision of the operational staff to change the control program.

Based on the values of the burnup B, cladding damage ω, and changes in the axial offset AO, it will be possible to search for exactly the control program that will currently ensure the control of the operation of the nuclear power unit [8, 9] in the best ratio of efficiency and reliability [10, 11].

For the case of operation of a nuclear power unit, the fuel burnup B acts as an efficiency parameter [12], while AO and ω are operation reliability parameters.

Since the criteria included in the objective function are multidirectional, that is, they strive to achieve different objectives and have absolute values that differ by an order of magnitude, first of all, it is necessary to normalize them [13, 14].

The normalized value of fuel burnup B is assumed from 0 to 1 and was calculated as follows:

$$B_{\text{norm}} = \frac{B_{\text{pow}}}{B_{\text{max}}}. \tag{5}$$

The cladding damage indicator does not need to be normalized, since its value [15] is in the range from 0 to 1.

The maximum possible value of the axial offset AO is 5 relative units, due to falling into the recommended area established by the regulations [16].

The normalized value is calculated by (6):

$$AO_{\text{norm}} = \frac{AO_{\text{pow}}}{AO_{\text{max}}}. \tag{6}$$

As is known, one of the conditions under which the optimization problem can be formulated and solved is the presence of a single, clearly formulated and quantitatively defined optimality criterion in the form of an objective function.

In the context of many objectives and limited resources, not all objectives can be achieved. In target programming, this possibility is provided, and a new type of variables is introduced to display it, showing the degree of deviation of the achieved level of objectives from the required one.

In general terms, the objective function will be written as follows [17]:

$$J = \sqrt{\kappa_1(B_{\text{norm}}\text{-}B^{'})^2+\kappa_2(\omega\text{-}\omega^{'})^2+\kappa_3(AO_{\text{norm}}\text{-}AO^{'})^2}, \quad (7),$$

where $B^{'}, \omega^{'}, AO^{'}$ are the objectives of each criterion; κ_1, κ_2, κ_3 are weighting coefficients, κ_1=κ_2=κ_3=1.

Due to the parity of the criteria included in the objective function, it was decided to leave the weight coefficients equal to one.

Within the framework of this task, the normalized values of the objectives are as follows: $B' = 1$, since the maximum value of the burnup is found; $\omega' = 0$, since the minimum value of the damage parameter is found; $AO^{'} = 0$, since the minimum deviation from the set value of the axial offset is found. From the point of view of reliability and safe operation of nuclear power plants [18], the values of the last two indicated values should be within the prescribed ranges.

Therefore, expression (7) can be simplified by excluding zero objectives:

$$J = \sqrt{\kappa_1(B-1)^2 + \kappa_2 \cdot \omega^2 + \kappa_3 \cdot AO^2}. \quad (8)$$

Thus, the solution of the optimization objective function will consist in minimizing the functional of *J*, and will be written as follows:

$$J(B,\ \omega, AO) \rightarrow min. \quad (9)$$

Having solved the tasks set, it will be possible to talk about the concept of “efficient operation”, that is, a solution that combines three incompatible components, but, nevertheless, is “useful” in terms of reliability and economic benefits. Such a solution from the point of view of multicriteria optimization problems is called Pareto optimal.

Thus, the objective function has become:

$$J = f(B(t_{\text{co}}^{\text{in}}; n; \tau_{\text{op}}); \omega(t_{\text{co}}^{\text{in}}; n; \tau_{\text{op}}); AO(t_{\text{co}}^{\text{in}}; n)).(10)$$

where $t_{\text{co}}^{\text{in}}$ is coolant temperature at the reactor core inlet, C°; n is neutron flux density; τ_{op} is operating time, hour.

METHOD FOR SWITCHING STATIC POWER CONTROL PROGRAMS

The input parameters of the power unit are as follows: the initial position of the control and protection system elements, of the turbine control valve, the initial value of the boric acid concentration.

The output adjustable parameters are axial offset, neutron power, electric power of the nuclear power unit, steam flow rate, steam pressure in the secondary circuit, saturation temperature, and coolant temperature [19].

Also, three separate single-circuit automatic power control systems [20] were synthesized, with the help of which one of the process dependent parameters is maintained:

T_{in} is the coolant temperature at the inlet to the reactor core; T_{av} is he average coolant temperature; P_2 is the steam pressure in the secondary circuit.

The control action for these parameters is the change in the boric acid concentration. Individually, these circuits work correctly.

With the help of these automatic control systems, three static control programs were studied for the same object – a nuclear power unit with a pressurized water reactor [21]. To study transient processes during the transition from one control program to another, a switch of these programs was added to the existing model of an automatic control system [22, 23].

When testing the idea of the possibility of choosing a control channel, a problem arose in the I-component of the PI controllers during direct switching. It turned out that each controller exerts its own control action on the control object through the program switch, and after the control object via the feedback line, a control error accumulates in the other two disconnected controllers, since these controllers are not connected to the control object. When another controller is connected, in relation to switching the static program, the total control action is transferred to the control object, which causes a peak change in the main process dependent parameters of the object [24, 25]. The values of other process dependent parameters in this case also exceed the range of permissible values, which can lead to an emergency situation [10, 26].

Fig. 4, Fig. 5 and Fig. 6 show graphs showing the response of controlled variables to switching static programs. From these graphs it can be seen that the controlled values increases when applying a step disturbance. *AO* departed by 7 %, T_{in} – by 35 rel. units, P_2 – by 10 rel. units.

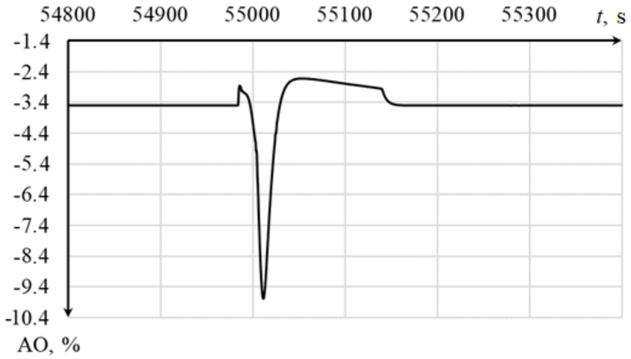

Fig. 4. **Graph of *AO* change when switching static programs**
Source: **compiled by the authors**

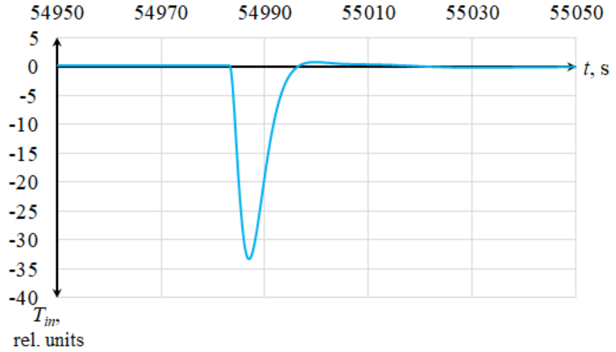

Fig. 5. **Graph of T_{in} change when switching static programs**
Source: **compiled by the authors**

In real conditions, the use of regulators also faced a similar problem. When switching from automatic control mode to manual control and vice versa, the value of the controlled variable increases. Therefore, it became necessary to implement a bumpless or smooth transition from one control mode to another [27]. Currently, regulators with a technically implemented smooth switching of control modes are used in industry [28].

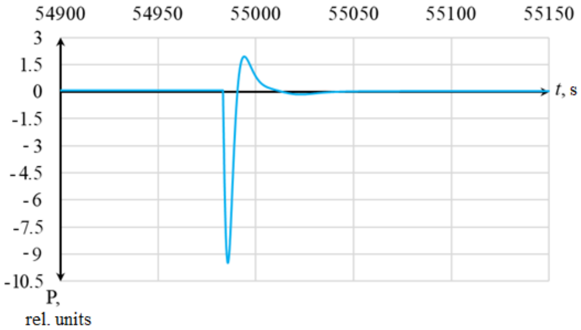

Fig. 6. **Graph of P_2 change when switching static programs**
Source: **compiled by the authors**

So, using the experience of smooth switching, it was possible to eliminate a surge in the simulation by adding additional feedback, indicated by a dotted line between the program switch and the controllers (Fig. 7). Thus, a smooth transition is obtained when switching from one control action to another.

Fig. 7 shows a simplified block diagram of the power unit and the control system for the main process parameters.

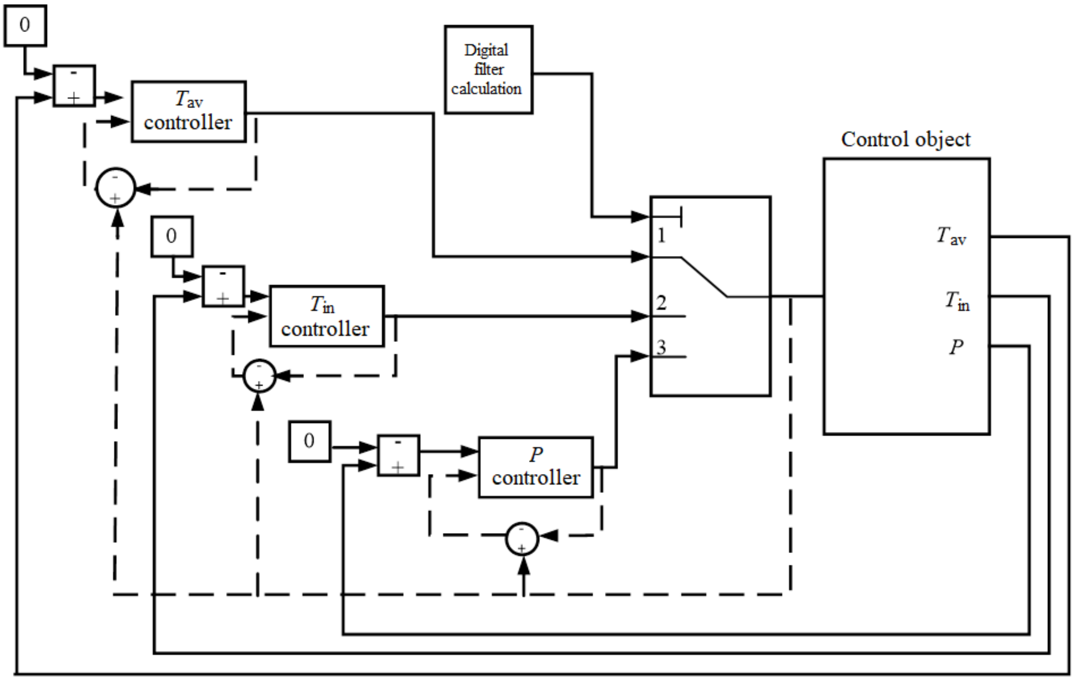

Fig. 7. **Block diagram of bumpless switching between static power control programs of a nuclear power unit with a pressurized water reactor**
Source: **compiled by the authors**

Thus, the possibility of bumpless switching [29] between these programs is implemented. The feedback of each of the regulators eliminates the control error. This made it possible to obtain a response to switching programs in the range of allowed deviations. Fig. 8, Fig. 9, Fig.10, Fig.11, Fig.12 and Fig. 13 show the response of process dependent parameters to a bumpless program switching at 80 % power of a nuclear power unit, as well as reaching 100 % power according to another control program.

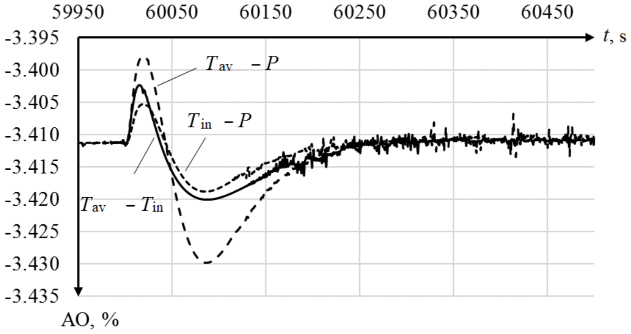

Fig. 8. **Axial offset response to direct switching of power control programs**
Source: **compiled by the authors**

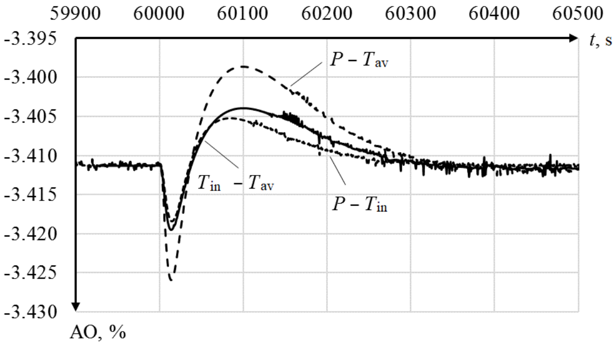

Fig. 9. **Axial offset response to reverse switching of power control programs**
Source: **compiled by the authors**

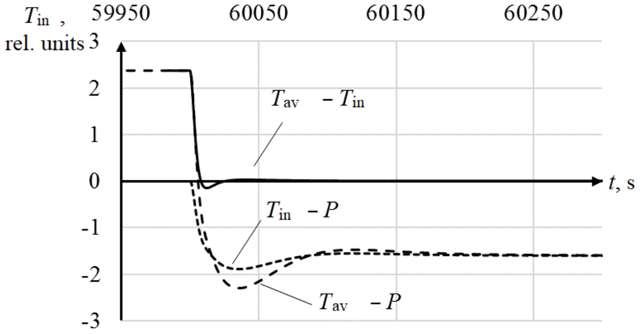

Fig. 10. **Response of coolant temperature at the core inlet to direct switching of power control programs**
Source: **compiled by the authors**

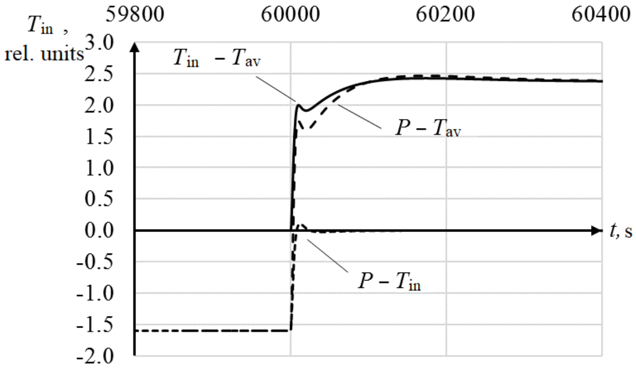

Fig. 11. **Response of coolant temperature at the core inlet to reverse switching of power control programs**
Source: **compiled by the authors**

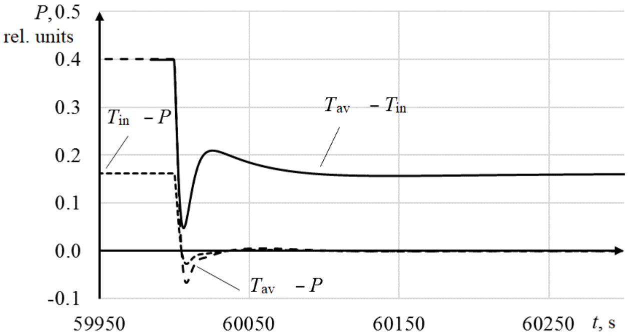

Fig. 12. **Steam pressure response in the secondary circuit to direct switching of power control programs**
Source: **compiled by the authors**

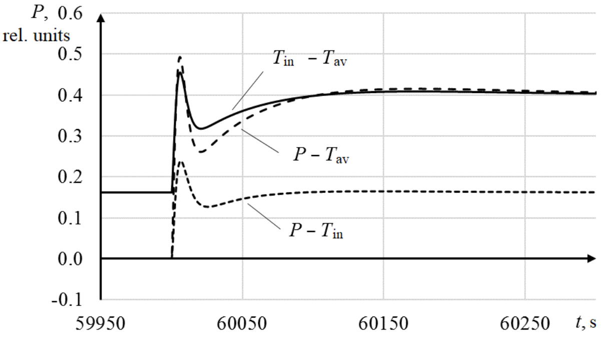

Fig. 13. **Steam pressure response in the secondary circuit to reverse switching of power control programs**
Source: **compiled by the authors**

An analysis of the data shown in Fig. 8, Fig. 9, Fig. 10, Fig.11, Fig.12 and Fig.13 showed that the maximum *AO* deviation was 0.015 % for direct switching, 0.027 % for reverse switching, and the control time was 300 s for direct switching and 400 s for reverse switching. The coolant temperature at the core inlet changed by 5 rel. units during 150 s during direct switching, and by 4 rel. units during reverse switching, the control time of which was 300 s. The maximum deviation of steam pressure during direct switching of programs was 0.45 rel. units, and 0.3 rel. units – during reverse. The transient period in both cases was 150 s.

The description of the problem-solving algorithm is presented below (Fig. 14).

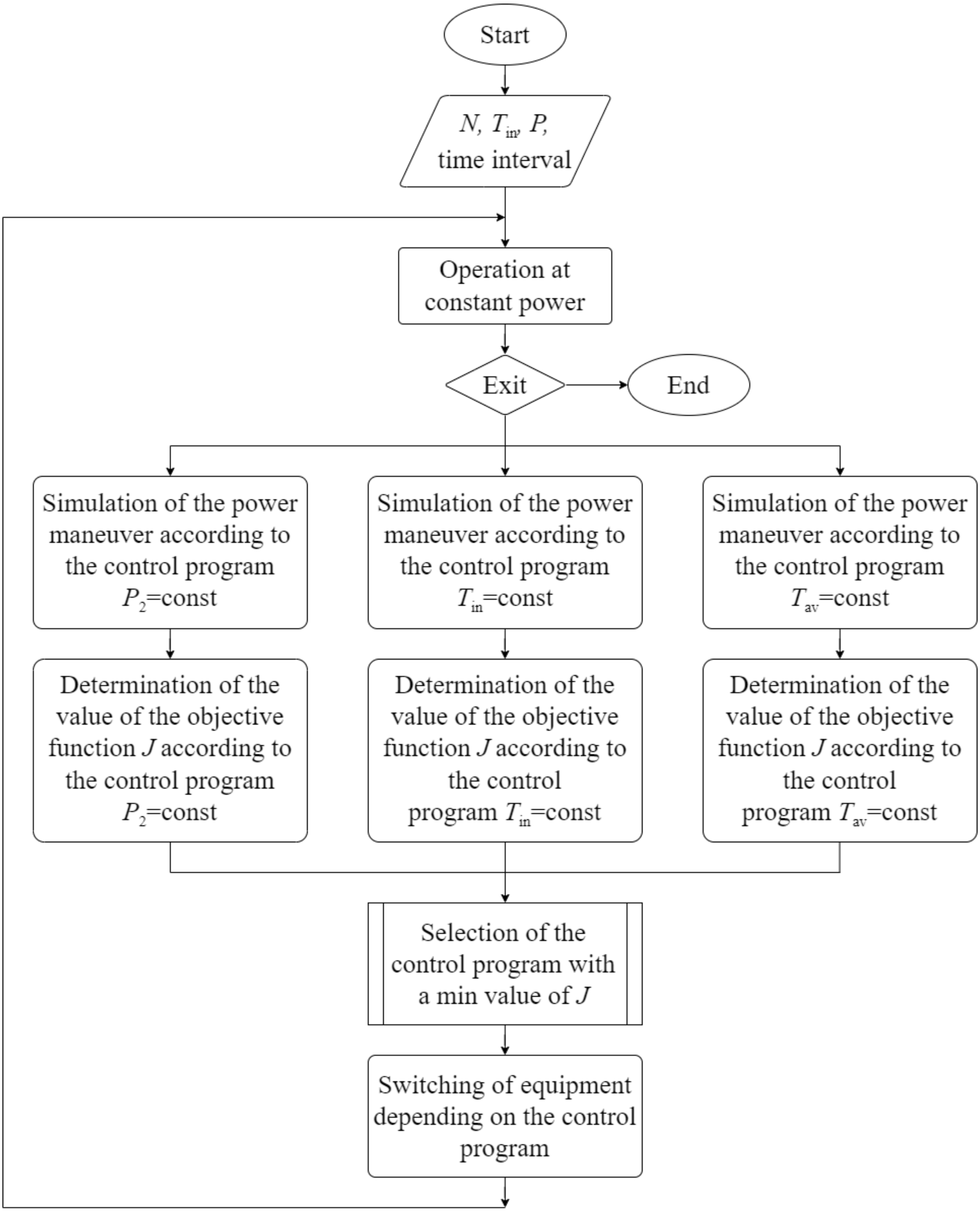

Fig. 14. **Algorithm for switching power control programs**

Source: **compiled by the authors**

This algorithm works in the prediction mode. So, first, the simulation of the operation of the reactor plant during the day in the maneuvering mode is carried out, reducing the power of the reactor plant to 80% at night and increasing it to 100 % at the beginning of the day. The reactor plant is operated according to one of the three control programs considered, namely, with a constant pressure in the secondary circuit, a constant temperature of the coolant at the inlet to the reactor core, and a constant average temperature of the coolant in the reactor.

For 15 hours, the power of the reactor plant is maintained constant at 100 %. Then, within 0.5 hours, by introducing a solution of boric acid into the reactor, the power is reduced to 90%. Next, the reactor is poisoned, due to which its power is reduced to 80 % in 2.5 hours. Further, the reactor plant is operated at 80 % power for 4 hours. At the same time, the value of the objective function J corresponding to one or another power control program is calculated. And this happens two more times for the remaining regulation programs. The values of J are compared with each other and the minimum is found. If the minimum value of J corresponds to the current power control program, the operation of the reactor plant during the next day will occur according to the same control program. If the minimum value of J corresponds to a different control program, then it will be necessary to switch the equipment and achieve 100 % power according to another control program within 2 hours. Then the cycle continues throughout the entire fuel cycle.

RESEARCH RESULTS

There are studies on optimization of the control program P_2=const by the objective function, which was based on the fuel burnup and axial offset. The obtained results of the control method minimize changes in the local energy release, accompanied by a change in the values of the reactor power and axial offset, which characterizes the uneven distribution of power over the height of the core [30].

From the point of view of the study, the uneven distribution of power affects the durability of the fuel cladding, which made it possible to introduce a characteristic into the optimization function that takes this into account. Moreover, for the first time, the optimal states of the characteristics of various control programs for the proposed objective function (10) have been studied.

Based on these data, the solution of the objective function was verified during 1 month of operation of the nuclear power unit according to the schedule of daily maneuvering, which is 11 switching’s (Fig. 15).

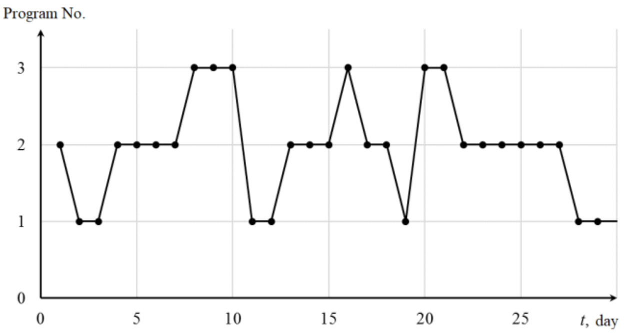

Fig. 15. **Schedule of switching power control programs during 1 month of maneuvers: 1 – T_{av}=const; 2 – T_{in}=const; 3 – P_2=const**

Source: **compiled by the authors**

The solution to the problem of optimizing the switching of static power control programs by searching for the optimal control program was obtained by comparing the following load history scenarios during a 4-year campaign (Table 2):

– 2 months in transition mode, 10 months in stationary mode (scenario I);

– 3 months in transition mode, 9 months in stationary mode (scenario II);

– 4 months in transition mode, 8 months in stationary mode (scenario III);

– 5 months in transition mode, 7 months in stationary mode (scenario IV);

– 6 months in transition mode, 6 months in stationary mode (scenario V).

Table 2. **The results of optimization of switching between static programs**

	Program name	Scenario number				
		I	II	III	IV	V
Number of switchings	T_{av}=const	20	33	35	38	54
	T_{in}=const	18	32	34	37	53
	For 4 years campaign	38	65	69	75	107

Source: **compiled by the authors**

Consequently, the solution of the objective optimization function is a different number of switching’s only between two static control programs T_{av}=const and T_{in}= const of the power of a nuclear power unit to ensure the optimal balance of safety and efficiency of operation of a nuclear power unit. Based on the obtained results, it is proved that daily power maneuvering according to the P_2=const program for more than one month is not optimal.

CONCLUSIONS

1. The simulation model of the automated power control system, based on the shockless switching of static programs according to the technological methods of operating power equipment, made it possible to form a change in the current model of the control program with the power of the control object in the range from 80 to 100 %, eliminate the static control error and obtain the response of technological parameters to switching programs in the range of allowed deviations.

2. An objective function is proposed, which includes three normalized criteria with different objectives: the maximum value of the fuel burnup, the minimum value of the fuel element cladding damage and the axial offset. This made it possible to combine multidirectional factors in one expression and find the best solution.

3. The problem of optimizing the switching of static power control programs is solved by minimizing the objective function, which combines such characteristics as the efficiency and safety of operation a nuclear power unit with a pressurized water reactor. This made it possible to switch static programs without shock during the reactor's fuel cycle in a daily load change cycle, minimizing current external and internal disturbances. Minimization of the objective function consists either in 11 switching’s between the static programs T_{av}=const, T_{in}=const, P_2=const during 1 month of daily maneuvers at the beginning of each year of the fuel cycle, or in 38; 65; 69; 75; 107 switching between the static programs T_{av}=const and T_{in}=const during the 4-year cycle at 2; 3; 4; 5; 6 months of maneuvers at the beginning of each year respectively.

REFERENCES

1. Fathy, E. & Hassanien, A. E. “Fuzzy harmonic mean technique for solving fully fuzzy multilevel multiobjective linear programming problems”. *Alexandria Engineering Journal*. 2022; 61 (10): 8189 – 8205. https://www.scopus.com/authid/detail.uri?authorId=57210996339. DOI: https://doi.org/10.1016/j.aej.2022.01.021.

2. Li, G., Wang, X., Liang, B., Li, X., Zhang, B. & Zou, Y. “Modeling and control of nuclear reactor cores for electricity generation. A review of advanced technologies”. *Renewable and Sustainable Energy Reviews*. 2016; 60: 116–128. https://www.scopus.com/authid/detail.uri?authorId=55547117794. DOI: https://doi.org/10.1016/j.rser.2016.01.116.

3. Wang, G., Wu, J., Zeng, B., Xu, Z., Wu, W. & Ma, X. “State-space model predictive control method for core power control in pressurized water reactor nuclear power stations”. *Nuclear Engineering and Technology*. 2016; 49: 134–140. https://www.scopus.com/authid/detail.uri?authorId=57192082917. DOI: http://dx.doi.org/10.1016/j.net.2016.07.008.

4. Ding, Y., Wang, Q., Tian, Z., Lyu, Y., Li, F., Yan, Z. & Xia, X. “A graph-theory-based dynamic programming planning method for distributed energy system planning: Campus area as a case study”. *Applied Energy*. 2023; 329: 120258. https://www.scopus.com/authid/detail.uri?authorId=36630321200. DOI: https://doi.org/10.1016/j.apenergy.2022.120258.

5. Maksimov, M. V., Kanazirskyi, N. F. & Kokol, E. A. “Control of the axial offset in a nuclear reactor at power maneuvering”. *Odes’kyi Politechnichnyi Universytet. Pratsi*. 2014; 2 (4): 75–81. DOI: https://doi.org/10.15276/opu.2.44.2014.15.

6. Petik, T., Vataman, V., Beglov, K. & Lysyuk, A. “Grounds for searching the best solution for controlling the pressurized water reactor in dynamic modes when changing the controlled parameters”. *Energy Engineering and Control Systems*. 2021; 7 (1): 56–61. DOI: https://doi.org/10.23939/jeecs2021.01.056.

7. Kokol, E. A. “Structural optimization of static power control programs for nuclear power plants with WWER-1000”. *Odes’kyi Politechnichnyi Universytet. Pratsi*. 2015; 3 (47): 41–46. DOI: https://doi.org/10.15276/opu.3.47.2015.07.

8. Foshch, T., Portela, F., Machado, J. & Maksimov, M. “Regression Models of the Nuclear Power Unit VVER-1000 Using Data Mining Techniques”. *Procedia Computer Science*. 2016; 100: 253–262. https://www.scopus.com/authid/detail.uri?authorId=57192589450. DOI: https://doi.org/10.1016/j.procs.2016.09.151.

9. Pelykh, S. N., Maksimov, M. V. & Ryabchikov, S. D. “The prediction problems of VVER fuel element cladding failure theory”. *Nuclear Engineering and Design*. 2016; 302: 46–55. https://www.scopus.com/authid/detail.uri?authorId=34971820000.
DOI: https://doi.org/10.1016/j.nucengdes.2016.04.005.

10. Pelykh, S. N., Maksimov, M. V. & Parks, G. T. “A method for VVER-1000 fuel rearrangement optimization taking into account both fuel cladding durability and burnup”. *Nuclear Engineering and Design*. 2013; 257: 53–60. https://www.scopus.com/authid/detail.uri?authorId=34971820000. DOI: https://doi.org/10.1016/j.nucengdes.2012.12.022.

11. Foshch, T., Machado, J., Portela, F., Maksimov, M. & Maksimova, O. “Comparison of two control programs of the VVER-1000 Nuclear power unit using regression data mining models”. *Nuclear and Radiation Safety*. 2017; 3 (75): 11–17. DOI: https://doi.org/10.32918/nrs.2017.3(75).02.

12. Pelykh, S. N., Maksimov, M. V. & Nikolsky, M. V. “A method for minimization of cladding failure parameter accumulation probability in VVER fuel elements”. *Problems of Atomic Science and Technology*. 2014; 92 (4): 108–116. – Available from: https://vant.kipt.kharkov.ua/ARTICLE/VANT_2014_4/ article_2014_4_108.pdf. – [Accessed: March 2022].

13. Pelykh, S. N. & Maksimov, M. V. “Theory of VVER-1000 fuel rearrangement optimization taking into accounts both fuel cladding durability and burnup”. *Problems of Atomic Science and Technology*. 2013; 44 (2) 84: 50–54. URL: http://dspace.nbuv.gov.ua/bitstream/handle/123456789/111678/08-Pelykh.pdf?sequence=1.

14. Yan, X., Wang, P., Qing, J., Wu, S. & Zhao, F. “Robust power control design for a small pressurized water reactor using an H infinity mixed sensitivity method”. *Nuclear Engineering and Technology*. 2020; 52 (7): 1443–1451. https://www.scopus.com/authid/detail.uri?authorId=57211839857. DOI: http://doi.org/10.1016/j.net.2019.12.031.

15. Pelykh, S. N. & Maksimov, M. V. “The method of fuel rearrangement control considering fuel element cladding damage and burnup”. *Problems of Atomic Science and Technology*. 2013; 87 (5): 84–90. – Available from: https://vant.kipt.kharkov.ua/ARTICLE/VANT_2013_5/article_2013_5_84a.pdf. – [Accessed: March 2022].

16. Maksimov, M. V., Pelykh, S. N. & Gontar, R. L. “Principles of controlling fuel-element cladding lifetime in variable VVER-1000 loading regimes”. *Atomic Energy*. 2012; 112 (4): 241–249. DOI: https://doi.org/10.1007/s10512-012-9552-3.

17. Kokol, E.A. “Optimal power control of VVER-1000 due to targeted selection of the control program” (in Russian). *Automation 2015: XXII International Conference on Automatic Control*. Odessa: Ukraine. 2015. p. 119–120.

18. Foshch, T., Maksimov, M., Pelykh, S. & Maksimova, O. “Models and methods for automated control of power change at VVER-1000 nuclear power unit”. *Nuclear and Radiation Safety*. 2018; 1 (77): 24–30. – Available from: http://dspace.opu.ua/jspui/bitstream/123456789/10580/1/ydpb_2018_1_6.pdf. – [Accessed: March 2022].

19. Odrekhovska, Y. O., Zhou, H. & Pelykh, S. N. “Optimization of switching of static power control programs for NPPs with VVER-1000 in transient operating modes” (in Russian). *XXIV Annual Scientific Conference of the Institute for Nuclear Research of the National Academy of Sciences of Ukraine: Abstracts*. Kiev: Ukraine. 2017. p. 123.

20. Foshch, T. & Pelykh, S. “Improved models and method of power change of NPP unit with VVER-1000”. *Automation of Technological and Business-Processes*. 2017; 9 (1): 56–66. DOI: http://dx.doi.org/10.15673/atbp.v9i1.505.

21. Plakhotnuk, A. A., Kokol, E. A. & Maksimov, M. V. “Improved PCS software switch control power generating” (in Russian). *Automation Technological and Business-Processes*. 2015; 7 (3): 26–33. DOI: https://doi.org/10.15673/2312-3125.4/2015.50429.

22. Brunetkin, O., Beglov, K., Maksymov, M., Baskakov, V., Vataman, V. & Kryvda, V. “Designing an automated control system for changing NPU energy release compensating for arising internal disturbing factors based on their approximation model”. *Eastern-European Journal of Enterprise Technologies*. 2022; 3 (2 (117): 63–75. DOI: https://doi.org/10.15587/1729-4061.2022.258394.

23. Maksymov, M., Alyokhina, S. & Brunetkin, O. “Thermal and reliability criteria for nuclear fuel safety”. *River Publishers (Verlag)*. 2021. 260 p. https://www.scopus.com/authid/detail.uri?authorId=7005088554. e-ISBN: 9788770224000.

24. Zhou, H., Pelykh, S. N., Odrekhovska, I. O. & Maksymova, O. B. “Optimization of power control program switching for a WWER-1000 under transient operating conditions”. *Problems of Atomic Science and Technology*. 2018; 1 (113): 218–221. – Available from:

http://dspace.nbuv.gov.ua/bitstream/handle/123456789/137360/36-Zhou.pdf?sequence=1. – [Accessed: March 2022].

25. Filimonov, P. E., Aver'yanova, S. P. & Filimonova, M. P. “Control of control-rod groups in the maneuvering regime of VVÉR-1000 operation” (in Russian). *Atomic Energy*. 1998; 84 (5): 383–387. DOI: https://doi.org/10.1007/BF02414876.

26. Ningbo, L. & Xueyao, S. “Research on the control of containment pressure of Gen II+ NPP under severe accident condition”. *Energy Procedia*. 2017; 117: 220–224. https://www.scopus.com/authid/detail.uri?authorId=57196222634.
DOI: https://doi.org/10.1016/j.egypro.2017.08.098.

27. Maksimov, M. V., Tsiselskaya, T. A. & Kokol, E. A. “The method of control of nuclear power plant with VVER-1000 reactor in maneuverable mode”. *Journal of Automation and Information Sciences*. 2015; 47 (6): 17–32. DOI: https://doi.org/10.1615/JAutomatInfScien.v47.i6.20.

28. Jiang, Q., Liu, Y., Zeng, W. & Yu, T. “Study on switching control of PWR core power with a fuzzy multimodel”. *Annals of Nuclear Energy*. 2020; 145: 107611. https://www.scopus.com/authid/detail.uri?authorId=57211412665.
DOI: https://doi.org/10.1016/j.anucene.2020.107611.

29. Plakhotnuk, A. A., Kokol, E. A. & Maksimov, M. V. “Simulation of changes in the structure of technical means of automation at the VVER-1000 while maneuvering” (in Russian). *Automation Technological and Business-Processes*. 2015; 7 (4): 64–71. DOI: https://doi.org/10.15673/2312-3125.24/2015.56334.

30. Aver’yanova, S. P., Vokhmyanina, N. S., Zlobin, D. A., Filimonov, P. E., Kuznetsov, V. I. & Lagovskii V. B. “Offset-cardinality phase diagram method of controlling reactor power”. *Atomic Energy*. 2017; 121: 155–160. DOI: https://doi.org/10.1007/s10512-017-0176-5.

Conflicts of Interest: the authors declare no conflict of interest

Received 07.04.2023
Received after revision 12.06.2023
Accepted 19.06.2023

DOI: https://doi.org/10.15276/hait.06.2023.9
УДК 621.039.56:681.5

Метод пошуку найкращої статичної програми регулювання ядерної енергетичної установки при виникненні збурень різної природи

Беглов Костянтин В'ячеславович[1)]
ORCID: https://orcid.org/0000-0002-5277-2577; beglovkv@gmail.com
Одреховська Євгенія Олександрівна[2)]
ORCID: https://orcid.org/0000-0003-3134-4204; jenia1991@i.ua
Петік Тая Володимирівна[1)]
ORCID: https://orcid.org/0009-0001-8817-1706; taiapetik@gmail.com
Ватаман Вікторія Володимирівна[1)]
ORCID: https://orcid.org/0000-0003-4403-5814; vataman043@gmail.com
[1)] Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна
[2)] Відокремлений підрозділ «Південноукраїнська АЕС», промисловий майданчик ВП ПАЕС.
м. Южноукраїнськ, Миколаївська обл., 55000, Україна

АНОТАЦІЯ

Враховуючи актуальний стан енергетики України в небезпечному та нестабільному середовищі, експлуатація АЕС є одним з найважливіших джерел забезпечення держави електроенергією. Під час експлуатації ядерної енергетичної установки в стаціонарному стані на неї діє багато внутрішніх збурень. Кількість зовнішніх збурень збільшується за умови експлуатації ядерної енергетичної установки в режимі добового циклу навантаження при воєнному стані, що призводить до коливань та зміни значень технологічних параметрів. Розвиток теорії оптимального керування та технічний рівень автоматизованих систем керування технологічними процесами, при поточному стані речей, дозволяють не знизити ефективність керування ядерною енергетичною установкою не тільки за рахунок зміни параметрів при будь якому навантаженні, а й за рахунок зміни структури технічних засобів автоматизації, що здатні реалізувати певну статичну програму регулювання потужності, що в поточний час нівелює впливи внутрішніх та зовнішніх збурень, без зменшення показників безпеки. Розглядається ситуація коли метод лінійного програмування не може бути застосовний для вирішення задачі регулювання. У даному випадку рішення на кожному етапі не залежить від рішення на попередньому. Саме тут у нагоді стає цільове програмування – це один з методів багатокритеріальної оптимізації, в теорії якої вирішуються завдання прийняття рішень одночасно за кількома критеріями. Метою роботи є забезпечення безпечної та ефективної експлуатації ядерної енергетичної установки в енергетичній системі, що не є постійною за експлуатаційними станами. Це досягається за рахунок пошуку найкращого методу перемикання статичних програм регулювання при завданні збурень різної природи. Використовуючи математичну модель ядерної енергетичної установки проведені досліди з моделювання переключень програм регулювання. В результаті отримано плавний перехід при перемиканні з одного керуючого впливу на інший. Імітаційна модель автоматизованої системи керування потужністю, яка заснована на безударному перемиканні статичних програм за технологічними методами експлуатації енергетичного обладнання, дозволила сформувати зміну поточної моделі програми регулювання, а також ліквідувати статичну помилку регулювання та одержати реакцію технологічних параметрів на перемикання програм. Також за результатами досліджень запропоновано цільову функцію, до складу якої входять три нормовані критерії з різними цілями. Зокрема вирішено задачу оптимізації перемикання статичних програм регулювання потужності за рахунок мінімізації цільової функції, яка об’єднує в собі такі характеристики, як економічність та безпека експлуатації ядерної енергетичної установки.

Ключові слова: Ядерний реактор; система керування; регулювання потужності; показники безпеки; паливна кампанія; статичні програми

ABOUT THE AUTHORS

Konstantin Vyacheslavovich Beglov - PhD in Engineering, Associate professor of the Department of Software and Computer-Integrated Technology. Odessa Polytechnic National University, 1, Shevchenko Av. Odessa. 65044, Ukraine
ORCID: https://orcid.org/0000-0002-5277-2577; beglovkv@gmail.com
Research field: Automation and control in technical systems; automated control systems in the field of nuclear power; automated control systems in the field of optimal burning gas fuel

Беглов Костянтин В'ячеславович - кандидат технічних наук, доцент кафедри Програмних і комп’ютерно-інтегрованих технологій. Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна

Yevhenia Oleksandrivna Odrekhovska - Engineer for Automated Production Control Systems at Department of Thermal Automation and Measurements of the Separate unit “Pivdennoukrainska NPP”, Industrial Site. Yuzhnoukrainsk, Mykolaiv Region, 55000, Ukraine
ORCID: https://orcid.org/0000-0003-3134-4204; jenia1991@i.ua
Research field: Switching of static power control programs for naps; maneuvering capabilities of the nuclear power plant

Одреховська Євгенія Олександрівна - інженер з Автоматизованих систем керування виробництвом цеху теплової автоматики та вимірювань, відокремленого підрозділу «Південноукраїнська АЕС», промисловий майданчик ВП ПАЕС. м. Южноукраїнськ, Миколаївська обл., 55000, Україна,

Taia Volodymyrivna Petik - PhD Student of the Department of Software and Computer-Integrated Technologies, Odessa Polytechnic National University, 1, Shevchenko Av. Odessa, 65044, Ukraine
ORCID: https://orcid.org/0009-0001-8817-1706; taiapetik@gmail.com
Research field: Automation and control in technical systems; automated control systems in the field of nuclear power; automatic control system in the field of heat exchangers

Петік Тая Володимирівна - аспірант кафедри Програмних і комп’ютерно-інтегрованих технологій, Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна

Viktoriia Volodymyrivna Vataman - PhD Student of the Department of Software and Computer-Integrated Technologies. Odessa Polytechnic National University, 1, Shevchenko Av. Odessa. 65044, Ukraine
ORCID: https://orcid.org/0000-0003-4403-5814, vataman043@gmail.com
Research field: Automatic control systems of process dependent parameters of nuclear reactor core; automated control systems in the field of nuclear power; automated control system of nuclear power plant under forced disturbances

Ватаман Вікторія Володимирівна - аспірант кафедри Програмних і комп’ютерно-інтегрованих технологій, Національний університет «Одеська політехніка», пр. Шевченка, 1. Одеса, 65044, Україна