UDC 621.039.5:681.5

OPTIMIZATION OF POWER CONTROL PROGRAM SWITCHING FOR A WWER-1000 UNDER TRANSIENT OPERATING CONDITIONS

Huiyu Zhou, S.N. Pelykh, I.O. Odrekhovska, O.B. Maksymova
Odessa National Polytechnic University, Odessa, Ukraine
E-mail: 1@pelykh.net; tel.: +38(066)187-21-45

This paper is devoted to solution of the scientific and technical problem of safe switching of static power control programs for a nuclear power unit with a WWER-1000 under transient operating conditions, so that to minimize the influence of disturbances of external and internal operating parameters, as well as to increase the safety and efficiency of reactor operation. The switching optimization task for static power control programs has been solved by finding a decision of the objective function which allows to switch safely the energy equipment modes in a predetermined range of load variations. The possibility of switching between static power control programs during a 4-year reactor campaign has been studied. The control program optimization problem for anuclear power unit with a WWER-1000 operated under variable loading, considering different power control programs during a 4-year campaign, has been solved.

INTRODUCTION

Considering the present state of power generation in Ukraine, operation of nuclear power plants (NPPs) with WWER-reactors is a long-term project to which Ukraine will remain committed for many years to come [1]. As there is a lack of load following units in the consolidated power system of Ukraine, in order to insure a sufficient level of electricity quality, NPPs with WWERs should participate in peak load and frequency regulation. Even if a WWER-1000 reactor is operated under stationary operating conditions, the reactor core is influenced by a number of disturbances having different nature and origin. But the number of disturbances influencing core stability, safety and efficiency is greatly increased when a reactor is operated under variable loading, e. g. according to a daily load variation cycle, as a reactor power maneuvering is characterized by considerably changing values of mainreactor technological parameters [2].

If a WWER-1000 is operated under variable loading, e.g. in the range 100…80% of the nominal reactor power N_0, reactor power control methods should be chosen based on solving an optimization task, because a power control method influences greatly on the power equipment operation and safety. The following WWER-1000 power control methods will be considered in this paper [3, 4]:

– core averaged coolant temperature is constant: $\langle t_W \rangle$ = const (program I);

– second circuit in let steam pressure is constant: p_2 = const (program II);

– core inlet coolant temperature is constant: $t_{W,0}$ = const (program III).

The modern state of optimal control theory and automated control systems allows us to control the reactor power, according to a daily load cycle, on the basis of changing both reactor technological parameters and the structure of automation equipment fulfilling a power control method.The main aim of this paper is to solve the optimization task in switching WWER-1000 power control programs under transient operating conditions, based on accounting for disturbances of technological parameters, as well as for the current state of the reactor equipment, in order to increase the competitive ability of NPPs with WWER-1000 reactors.

OBJECTIVE FUNCTION COMPONENTS

Following the method of construction of the WWER-1000 fuel assembly (FA) rearrangement efficiency criterion proposed in [4, 5], the objective function for optimization of switching between reactor power control programs includes such variables:

– axial offset module $|\mathrm{AO}|$ (for simplicity, herein after the module sign for AO can be omitted) as a measure of neutron flux stability in the reactor core, that is a measure of both safety and efficiency of reactor core and fuel operation;

– nuclear fuel burn up (*B*) as a measure of fuel operation efficiency;

– cladding damage parameter (ω) as a measure of both safety and efficiency of fuel operation;

The value of axial offset is determined by the ratio of the difference between heat powers of higher (Q_h) and lower (Q_l) parts of the core, to the total heat power of the core:

$$\mathrm{AO}(\tau) = \frac{Q_h(\tau) - Q_l(\tau)}{Q_h(\tau) + Q_l(\tau)} \cdot 100\ \%, \qquad (1)$$

where τ is time.

The value of nuclear fuel burn up is determined by the equation:

$$B_{i,j}(\tau) = \frac{1}{m}\int_0^{\tau} Q_{i,j}(t) \cdot dt, \qquad (2)$$

where $Q_{i,j}$ is heat power of the *i*-th axial segment of a fuel element (FE) averaged in the *j*-th FA, W; *m* is mass of the nuclear fuel in the corresponding axial segment, kg.

The value of cladding damage parameter is determined by the equation [6, 7]:

$$\omega(\tau) = A(\tau)/A_0;\ A(\tau) = \int_0^{\tau} \sigma_e(\tau) \cdot \dot{p}_e(\tau) \cdot d\tau, \qquad (3)$$

where $A(\tau)$ is specific dispersion energy (SDE), J/m³; A_0 is the value of SDE at the moment τ_0 that cladding material failure starts; $\sigma_e(\tau)$ and $\dot{p}_e(\tau)$ are equivalent stress (Pa) and rate of equivalent creep strain (s^{-1}), respectively, for the inner most cladding radial element having the maximum temperature; A_0 is constant for a given material of cladding and does not differ for operating modes, the calculated value of A_0 is 55 MJ/m^3 for a FE cladding made of Zircaloy-4 alloy [4].

The objective function for optimization of WWER-1000 power control program switching is based on the criterion model of FE behavior control taking into account safety and economic requirements simultaneously [4]. So, the objective function for optimization of WWER-1000 power control program switching has been constructed using the following principles [8]:

1. The goal for optimization of reactor power control program switchingis an increase of both safety and efficiency when operating the reactor core under normal conditions, by means of simultaneous consideration of axial offset, nuclear fuel burnup and cladding damage parameter.
2. Optimization of reactor power control program switchingis carried out on the basis of a priori requirements for FE and core behavior.
3. Advantage of some reactor power control program over another is determined on the basis of summation of advantages given by the dimensionless normalized components $(\mathrm{AO}^*, B^*, \omega^*)$ of the objective function J.
4. The physical meaning of the objective function J for optimization of WWER-1000 power control program switching is that if any of the dimensionless normalized components $(\mathrm{AO}^*, B^*, \omega^*)$ of J lies out of the corresponding permissible range, then this component gives a negative contribution to the total efficiency defined by the following equation for the objective function [9]:

$$J = \sqrt{(B^*-1)^2 + \omega^{*2} + \mathrm{AO}^{*2}}, \tag{4}$$

where $B^* = B / B^{\mathrm{lim}}$; $\omega^* = \omega / \omega^{\mathrm{lim}}$; $\mathrm{AO}^* = \mathrm{AO} / \mathrm{AO}^{\mathrm{lim}}$, where a priori requirements are: $B^{\mathrm{lim}} = 88$ (MW·d)/kg U; $\omega^{\mathrm{lim}} = 1$; $\mathrm{AO}^{\mathrm{lim}} = 0{,}05$.

So, the problem of control program optimization for a nuclear power unit with a WWER-1000 reactor operated under variable loading, during a 4-year campaign, was solved by minimization of J functional:

$$J(B^*, \omega^*, \mathrm{AO}^*) \to \min. \tag{5}$$

Taking into account that the components $(\mathrm{AO}^*, B^*, \omega^*)$ of J are mainly determined by core inlet coolant temperature $t_{\mathrm{W},0}$, neutron flux density n, n/(cm^2·s) and fuel service life τ [6], the minimum of the objective function was found using the method of quickest descent [9].

CALCULATION ASSUMPTIONS

Such calculation assumptions were accepted in this paper:

– WWER-1000 FE, FA, core operating and design parameters were assigned in compliance with the design characteristics [10], though the FE cladding material was Zircaloy-4 and accordingly the MATPRO-A cladding corrosion model was used [11];

– "Reactor simulator" code was used for calculation of linear heat rates in axial segments of a FA–averaged FE [12];

–"Femaxi" code was used to calculate the evolution of stresses and strains in FE claddings [11, 13];

– "Advanced" power control algorithm was considered and thus the lay out of regulating units was set according to the method described in [4, 14];

– N = 100 % → N = 80 % →N = 100% daily loading cycle was considered, where N is core power [4, 5];

– time dependences for N and the axial coordinate H of the lower edge of control elements of regulating units were set according to the method described in [6, 14];

– if core coolant in let temperature stays constant during a power maneuvering, it equals to 287 ºC;

– composition of nuclear fuel was set for the start of the 5-th campaign of Khmelnitskyi NPP, Unit 2 [4, 6];

– FA rearrangement model was based on modelling rearrangements of FAs in a core segment containing 1/6 of FAs placed in the core and 1/6 of regulating units used for reactor power maneuvering [8];

– distribution of FAs within a 1/6 core segment was set based on the albums of neutron-physical characteristics of the core [15], according to the method [14];

– calculation model of the power density distribution in fuel assembly – averaged FEs was based on a two-group neutron diffusion model [16];

– in order to account for most unfavourable cladding operation conditions, values of $\omega(\tau)$ and $B(\tau)$ included in the objective function J were calculated for the 6-th axial segment of a FA–averaged FE, consideringa FE located in a FA transposed in a 1/6 core segment according to the A rearrangement algorithm 3 (core cell) →22→54→29 characterized by most extreme conditions for FE claddings [8, 14]. Also the distribution of $\omega(t)$ among FEs included in this FA was taken into account by multiplying linear heat rates (calculated for axial segments) by the volume power-density irregularity coefficient 1.6 [14].

RESULTS

Using the "Reactor simulator" code which is an universal instrument for modeling of WWER-1000 operation, first of all stability of neutron flux and power release processes in a core during a 4-year reactor campaign, under reactor power maneuvering conditions according to N = 100 % → N = 80 % → N = 100% daily loading cycle, has been studied.

For reactor power control programs I, II, and III, core averaged coolant temperature $\langle t_{\mathrm{W}} \rangle$, second circuit in let steam pressure p_2 and core inlet coolant temperature $t_{\mathrm{W},0}$ were kept constant, respectively. Based on the requirement $\mathrm{AO}^{\mathrm{lim}} = 0.05$, the duration of reactor power maneuvering permissible for different power control programs, has been found. It was obtained that AO and the axial profile of neutrons stay stable during 7, 1, and 6 months for programs I, II, and III, respectively (Tabl. 1).

Table1

Permissible duration of reactor power maneuvering

Reactor power control program	Duration, months
I (<t_W> = const)	7
II (p_2 = const)	1
III ($t_{W,0}$ = const)	6

The calculated AO dependence on time for reactor power control program I (<t_W> = const) is shown in Fig. 1.

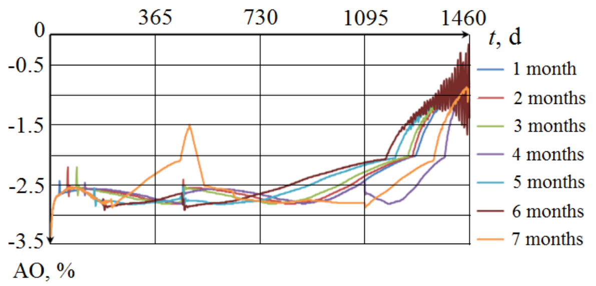

Fig. 1. Axial offset dependence on time for WWER-1000 power control program I

It can be seen that the amplitude of AO change in creases when the duration of reactor power maneuvering with <t_W> = const increases also, though AO stays in the permissible ranges: [–5; 2.5] and [–5; 4] for N = 100 and 80%, respectively [12].

The calculated AO dependence on time for reactor power control program II (p_2 = const) is shown in Fig. 2.

It can be seen that the amplitude of AO change exceeds the permissible range when the duration of reactor power maneuvering with p_2 = const exceeds one month, though the value of AO returns to permissible values and goes on staying in the permissible range after a reactor has been transferred from the mode of variable loading to the stationary mode.

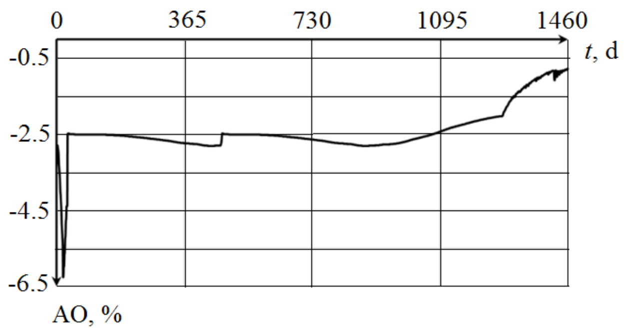

Fig. 2. Axial offset dependence on time for WWER-1000 power control program II

The calculated AO dependence on time for reactor power control program III ($t_{W,0}$ = const) is shown in Fig. 3.

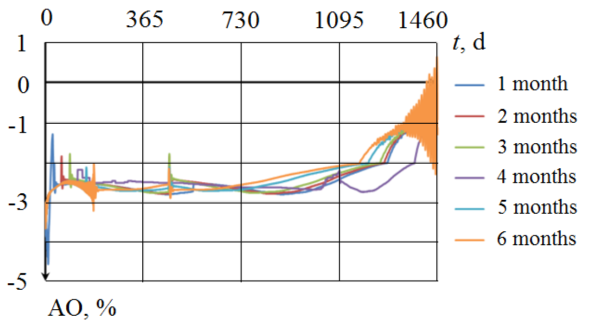

Fig. 3. Axial offset dependence on time for WWER-1000 power control program III

As it follows from Fig. 3, the amplitude of AO change increases when the duration of reactor power maneuvering with $t_{W,0}$ = const increases also, though AO stays in its permissible ranges.

Using the “Femaxi” code, other components ($B*$ and $\omega*$) of the objective function J, for reactor power control programs with <t_W> = const, p_2 = const, and $t_{W,0}$ = const, have been found. The calculated dependence of burn up B on time for programs I, II, and III is shown in Fig. 4.

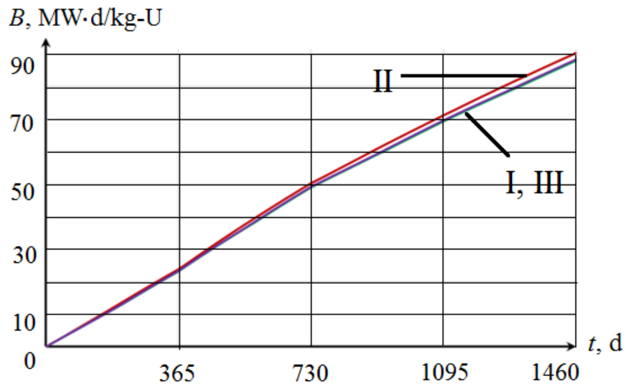

Fig. 4. Burn up dependence on time for WWER-1000 power control program I (<t_W>=const), II (p_2=const), and III ($t_{W,0}$=const)

It can be seen that the dependences of burn up on time for programs I and III are practically similar, while program II is characterized by a slightly greater value of burn up.

The calculated dependence of cladding damage parameter ω on time for programs I, II, and III is shown in Fig. 5.

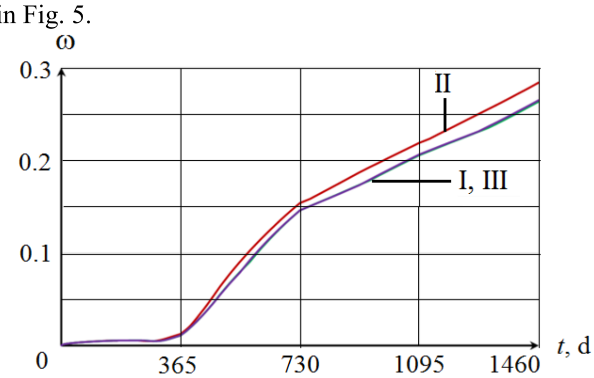

Fig. 5. Cladding damage parameter dependence on time for WWER-1000 power control program I (<t_W>=const), II (p_2=const), and III ($t_{W,0}$=const)

So, the dependences of cladding damage parameter ω on time for programs I and III are similar also, but program II is characterized by a greater valueof ω.

Having found stable operating regimes for a WWER-1000 operated under daily variable loading according to power control programs I, II, and III, the problem of control program optimization during a 4-year campaign was solved by minimization of J functional.

If the duration of reactor power maneuvering is one month, and further a WWER-1000 is operated under stationary loading conditions during 11 months, then the reactor peration will be optimal, from the point of view of both safety and efficiency, when 11 transitions between power control programs are made (Fig. 6).

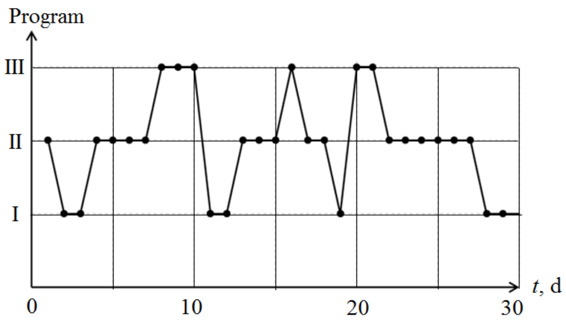

Fig. 6. Schedule of transitions between power control programs for one month of power maneuvering

Also the solutions of the objective function J have been found for the following WWER-1000 loading scenarios during a 4-year reactor campaign:

– 2 months of reactor power maneuvering, 10 months under stationary loading conditions (scenario 1);

– 3 months of reactor power maneuvering, 9 months under stationary loading conditions (scenario 2);

– 4 months of reactor power maneuvering, 8 months under stationary loading conditions (scenario 3);

– 5 months of reactor power maneuvering, 7 months under stationary loading conditions (scenario 4);

– 6 months of reactor power maneuvering, 6 months under stationary loading conditions (scenario 5).

Considering these loading scenarios, for a reactor under transient operating conditions according to $N = 100\% \rightarrow N = 80\% \rightarrow N = 100\%$ daily loading cycle, the calculated optimal number of transitions between power control programs I and III, is shown in Tabl. 2.

Table 2

The optimal number of transitions between programs I and III

Scenario	1	2	3	4	5
Number of transitions	38	65	69	75	107

Program II is not considered in Tabl. 2 because the permissible duration of WWER-1000 power maneuvering for this program is one month only.

CONCLUSIONS

As optimization of WWER-1000 power control program switching is one of important directions for improvement of both safety and efficiency of reactor operation under transient operating conditions according to the daily loading cycle $N = 100\% \rightarrow N = 80\% \rightarrow N = 100\%$, the optimization task in switching between reactor power control programs has been solved based on accounting for disturbances of axial offset as a measure of neutron flux stability in a core, nuclear fuel burnup as a measure of fuel operation efficiency, as well as cladding damage parameter as a measure of both safety and efficiency of nuclear fuel operation.

The duration of reactor power maneuvering permissible from the point of view of AO stability, for reactor power control programs I ($\langle t_W \rangle = \text{const}$), II ($p_2 = \text{const}$), and III ($t_{W,0} = \text{const}$) is 7, 1, and 6 months, respectively.

If the duration of WWER-1000 reactor power mane uvering is 1 month only, then the reactor operation will be optimal, fromthe point of view of both safety and efficiency, when 11 transitions between power control programs I, II, and III are made.

If the duration of WWER-1000 reactor power maneuvering is 2, 3, 4, 5, and 6 months, then the reactor operation will be optimal, from the point of view of both safety and efficiency, when 38, 65, 69, 75, and 107 transitions between power control programs I and III are made, respectively.

REFERENCES

1. N.I. Vlasenko. A long-term evaluation of nuclear power engineering development in Ukraine // *Proc. of the XX nd Int. Conf. on Physics of Radiative Effects and Radiative Study of Materials*, Alushta, NSC “Kharkov Institute of Physics and Technology”. 2012, p. 7-8.

2. H. Zhou, S.N. Pelykh, T.V. Foshch, O.B. Maksymova. An improved method for automated control of the WWER-1000 power maneuvering // *Problems of Atomic Science and Technology*. *Series “Physics of Radiation Effect and Radiation Materials Science”*. 2017, N 5(111), p. 57-64.

3. F.Y. Ovchinnikov, V.V. Semenov. *The operating regimes of water-water power reactors*. M.: “Energoatomizdat”, 1988, 359 p.

4. S.N. Pelykh, M.V. Maksimov, V.E. Baskakov. Grounds of WWER-1000 fuel cladding life control // *Annals of Nuclear Energy*. 2013, N 58, p. 188-197.

5. S.N. Pelykh, M.V. Maksimov, G.T. Parks. A method for WWER-1000 fuel rearrangement optimization taking into account both fuel cladding durability and burnup // *Nuclear Engineering and Design*. 2013, v. 257, N 4, p. 53-60.

6. S.N. Pelykh. *Grounds of WWER fuel element behavior control*. Saarbrücken: “Palmarium Academic Publishing”, 2013, 160 p.

7. O.V. Sosnin, B.V. Gorev, A.F. Nikitenko. *The energy variant of creep theory*. Novosibirsk: “The Siberian Branch of USSR Academy of Sciences”, 1986, 95 p.

8. S.N. Pelykh, M.V. Maksimov, M.V. Nikolsky. A method for minimization of cladding failure parameter accumulation probability in WWER fuel elements // *Problems of Atomic Science and Technology. Series “Physics of Radiation Effect and Radiation Materials Science”*. 2014, N 4, p. 108-116.

9. S.N. Pelykh, E.O. Odrekhovska, O.B. Maksymova. Search for the best power control program at NPP with WWER-1000 using gradient descent method // *Automation of technological and businessprocesses*. 2016, v. 8, N 3, p. 36-40.

10. V.D. Shmelev, Y.G. Dragunov, V.P. Denisov. *The WWER Active Cores for Nuclear Stations*. M.: "Aka-demkniga", 2004, 220 p.

11. M. Suzuki. *Light Water Reactor Fuel Analysis Code FEMAXI-V (Ver.1). JAERI-Data/Code 2000-030*. Tokai: "Japan Atomic Energy Research Institute", 2000, 285 p.

12. P.E. Philimonov, V.V. Mамichev, S.P. Averyanova. The "Reactor simulator" code for modeling of Maneuvering WWER-1000 regimes // *Atomnaya Energiya*. 1998, N 6, p. 560-563 (in Russian).

13. M. Suzuki. *Modelling of Light-water Reactor Fuel Element Behaviour in Different Loading Regimes*. Odessa: "Astroprint", 2010, 248 p.

14. S.N. Pelykh, M.V. Maksimov, S.D. Ryabchikov. The prediction problems of WWER fuel element cladding failure theory // *Nuclear Engineering and Design*. 2016, v. 302, Part A (June), p. 46-55.

15. R.Y. Vorobyev. *Albums of neutron-physical characteristics of the reactor core, Unit 5, Zaporizhzhya NPP. Campaigns 20−23*. Energodar: "Zaporizhzhya NPP", 2011, 323 p.

16. S.N. Pelykh, M.V. Maksimov. Cladding rupture life control methods for a power-cycling WWER-1000 nuclear unit // *Nuclear Engineering and Design*. 2011, v. 241, p. 2956-2963.

Article received 20.11.2017

ОПТИМИЗАЦИЯ ПЕРЕКЛЮЧЕНИЯ ПРОГРАММ РЕГУЛИРОВАНИЯ МОЩНОСТИ ВВЭР-1000 В ПЕРЕХОДНЫХ РЕЖИМАХ ЭКСПЛУАТАЦИИ

Х. Чжоу, С.Н. Пелых, Е.А. Одреховская, О.Б. Максимова

Статья посвячена решению научно-технической проблемы безопасрного переключения статических программ регулирования ядерного энергоблока с ВВЭР-1000 в переменных режимах нагружения, чтобы минимизировать влияние отклонений внешних и внутренних эксплуатационных параметров, а также повысить безопасность и эффективность эксплуатации реактора. Задача оптимизации переключений статических программ регулирования решена путем нахождения экстремума целевой функции, что позволяет безопасно переключать режимы эксплуатации энергетического оборудования в предусмотренном интервале изменения нагрузки. Изучена возможность переключения статических программ регулирования в течение 4-годичной кампании реактора. Рассматривая различные программы регулирования мощности ядерного энергоблока с ВВЭР-1000 в переменном режиме нагружения, решена задача оптимизации выбора программы на протяжении 4-годичной кампании.

ОПТИМІЗАЦІЯ ПЕРЕМИКАННЯ ПРОГРАМ РЕГУЛЮВАННЯ ПОТУЖНОСТІ ВВЕР-1000 У ПЕРЕХІДНИХ РЕЖИМАХ ЕКСПЛУАТАЦІЇ

Х. Чжоу, С.М. Пелих, Є.О. Одреховська, О.Б. Максимова

Стаття присвячена вирішенню науково-технічної проблеми безпечного перемикання статичних програм регулювання ядерного енергоблоку з ВВЕР-1000 у змінних режимах навантаження, щоб мінімізувати вплив відхилень зовнішніх і внутрішніх експлуатаційних параметрів, а також підвищити безпеку і ефективність експлуатації реактора. Завдання оптимізації перемикань статичних програм регулювання вирішене шляхом знаходження екстремуму цільової функції, що дозволяє безпечно перемикати режими експлуатації енергетичного обладнання в передбаченому інтервалі зміни навантаження. Вивчена можливість перемикання статичних програм регулювання протягом 4-річної кампанії реактора. Розглядаючи різні програми регулювання потужності ядерного енергоблоку з ВВЕР-1000 у змінному режимі навантаження, вирішена задача оптимізації вибору програми протягом 4-річної кампанії.