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To cite this article: B Djaroum *et al* 2020 *J. Phys.: Conf. Ser.* **1689** 012028

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Water exchange amount reduction algorithm for power control of VVER-1200 reactor operating in load-following mode

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Abstract. In order to solve the problem of water exchange minimization in the primary loop of VVER-1200 reactor operating in load-following mode, we chose the dynamic programming method (DPM). However, this method is very expensive in terms of RAM and computing time. A heuristic is introduced for the DPM to decrease the computational costs. The introduction of the heuristics makes it possible to cut the inefficient branches of the DPM algorithm and to increase its speed without loss of precision. In the proposed algorithm, the use of temperature regulation control reduces the amount of coolant removed from the reactor primary loop, the movement of control rods is limited, which keeps the current axial offset (AO) in the recommended area, makes it possible to equalize the energy release in the reactor core volume. The simulation results obtained confirm the improvement of reactor power control in terms of load following: deviation of core power from the load schedule is reduced, water exchange is decreased by more than 50%, which is useful from the point of view of liquid waste management and treatment.

1. Introduction

Recently, Load following mode is the potential for a nuclear power plant (NPP) to adjust its power output as demand and price for electricity fluctuates. At the same time, electricity suppliers are forced to improve the operational capabilities of their nuclear power plants in order to adapt production to daily or seasonal changes in electricity demand. Although in Russia the average of nuclear energy generation in electrical energy is only 20%, in some parts of the country energy the nuclear power plants contribution is much higher. This means that the issue of operating NPP power units in a maneuverable mode to ensure the stable operation of the power system must be considered.

However, the lack of experience in operating NPPs with VVER in load-following mode complicates the acquisition of experimental data on these modes, so the only way is the computational modeling using modern computational programs. In our case, for the transient processes' simulation, the PROSTOR software package was chosen [1]. The program is designed to carry out calculations of interrelated neutronic and thermohydraulic processes in the VVER-1200 reactor. Using this program, heuristic control algorithms were tested, designed to accelerate the optimization problem solution of reducing water exchange during the NPP operation with VVER reactor.



To solve the problem of minimizing water exchange in the first loop of a VVER-1200 reactor operating in load-following mode, the dynamic programming method (DPM) was used [2], [3]. DPM in mathematics and computer theory is a method for solving problems with an optimal substructure and overlapping subproblems, which is much more efficient than solving “head-on”. To find the solution of a given problem with this method, the problem is divided into stages, each subproblem set is solved, for which a set of restrictions is considered accordingly. This allows finding a step-by-step solution using the information obtained in the previous steps. The DPM has an important advantage: it is easy to take into account all possible restrictions, in particular, restrictions on the phase coordinates, which are more difficult for other methods. Besides, when applying the DPM, the phase constraints is reduced simply to checking and discarding them in the process of enumerating those trajectories that do not satisfy them.

The main difficulty of the numerical solution of the optimization problem with the help of the DPM requires a computer memory for storing the states’ history and a large number of calculations even with a relatively small number of phase coordinates. This difficulty is sometimes called the “curse of dimensionality”, which is the main obstacle to the application of DPM.

In order to reduce the computational costs using the DPM, a heuristic was introduced that allows to cut off ineffective branches in the DPM algorithm and increase its performance without losing accuracy.

This article describes a heuristic algorithm to minimize water exchange in the VVER-1200 reactor primary loop operating in load-following mode. Before proceeding to the algorithms examination for controlling the VVER-1200 reactor power, it is imperative to recall in general the possibilities and peculiarities of reactor power control.

2. Control actions in VVER-1200 reactor

Control actions in the VVER-1200 reactor are the movement of control rod groups in the reactor core, the boric acid concentration changes in the coolant by introducing distilled water (distillate) or boric acid into the primary loop, the coolant temperature changes in the inlet of the reactor (temperature control) and steam flow changes to the turbine [4], [5], [6].

The movement of control rod groups causes deformation of the energy release field in the core, which affects the safety of fuel operation. The water exchange is accompanied by the costs of processing the withdrawn coolant. However, there is a way to reduce the amplitudes of the given control actions using temperature control. It should be added that a change in the energy release in the core leads to a change in the xenon concentration and can excite relatively slow xenon transient processes lasting more than a day, which in turn affects the energy release in the core [7].

2.1 Displacement of control rod groups

The movement of the control rods (groups 12-11-10) allows maintaining a safe level of energy release in the reactor core. When controlling power, the displacement of the control rods with an interception in height is used. The operating speed of the control rod is 2 cm/s, its displacement affects the energy release field, which can lead to local overheating of the fuel cells.

For the purpose of automatic power change, an automatic power regulator (APR) is used, operating in the following control modes:

- H: mode of astatic maintenance of neutron power in the range from 3 to 100% at nominal power (W_N) of the reactor with a dead zone of no more than $\pm 1\% W_N$ and maintaining accuracy no worse than $2\% W_N$;
- T: mode of astatic maintenance of steam pressure in the main steam collector (MSC) with a dead zone of $\pm 0,05$ MPa in the range from 20 to 101% W_N . The accuracy of maintaining in stationary modes is 0.1 MPa;
- C: guarding mode. In this mode, the control rod groups move downward when the steam pressure in the MSC exceeds the nominal value by 0,19 MPa;
- Toprch: mode of primary frequency regulation by hardware.

The choice of the control mode (H, T, C or Toprch) is carried out by the operator. However, the existing APR is not always effective to provide regulated power to the load of reactor operating in load-following mode.

2.2 Boric acid concentration

Compensation for nuclear fuel burnout is carried out by changing the concentration of boric acid in the primary coolant through water exchange. Thus, the reactor power is reduced by introducing boric acid and increased by introducing distillate in the primary loop. Water exchange can be accompanied by the accumulation of radioactive waste, since the liquid removed from the primary loop is radioactive.

Concerning this, the problem arises of optimizing reactor power control to reduce water exchange [8]. The boric acid concentration change in the primary loop is described by the equation:

$$\frac{\partial C(t)}{\partial t} = \frac{G}{V\rho} (C_{\text{load}} - C(t)) \quad (1)$$

$$C(t)|_{t=0} = C_0$$

Where:

- $C(t)$: boric acid current concentration in the reactor primary circuit, g / kg;
- C_0 : boric acid current concentration in the reactor primary circuit at the start of water exchange operation, g / kg;
- C_{load} : introduced water concentration (either distillate, 0 g / kg or boric acid, 40 g / kg) for the sixth unit of the Novovoronezh NPP;
- G : water exchange rate, t / h;
- V : volume of primary coolant (~300 m³);
- ρ : density of primary coolant, kg / m³.

Hence, the boric acid concentration in the primary circuit and the mass of liquid removed from the primary circuit are determined as follows:

$$C = \exp\left(\frac{G\Delta t}{V\rho}\right) \times \left[C_{\text{load}} \left(\exp\left(\frac{G\Delta t}{V\rho}\right) - 1 \right) + C_0 \right] \quad (2)$$

$$G\Delta t = V\rho \ln \left[\frac{C_{\text{load}} - C_0}{C_{\text{load}} - C} \right] \quad (3)$$

Where:

- Δt : time of water exchange operation, hours;
- C : boric acid concentration in the primary loop at the end of water exchange operation, g / kg.

2.3 The temperature at the reactor core inlet

The change in the coolant temperature at the reactor core inlet with a constant pressure in the secondary loop for the VVER-1200 reactor depends on the power as follows [9]:

$$T = W \frac{(T_N - T_{\text{MCL}})}{(W_N - W_{\text{MCL}})} + T_{\text{MCL}} \quad (4)$$

Where:

- T : coolant temperature at the reactor inlet, °C;
- W : current reactor power, %;

- T_N : coolant temperature at the reactor inlet at its nominal power, 296,2 °C;
- T_{MCL} : coolant temperature at the reactor inlet at the minimum controlled power level (MCL): 285,0 °C;
- W_N - nominal power reactor 100%;
- W_{MCL} : minimum controlled power level, 0%.

Coolant temperature changes (T) and steam pressure in the second loop (P) at constant reactor power are described by equation (5), i.e. a pressure change by $\Delta P = 0,1$ MPa causes a change of coolant temperature approximately by $\Delta T = 1$ °C:

$$\Delta T = 9,5(P - P_N) \quad (5)$$

Where:

- P : current steam pressure in the second loop, MPa;
- P_N : steam pressure in the second loop at nominal power: 6,8 MPa.

Thus, the coolant temperature dependence of the power and pressure in the second loop can be represented as follows:

$$T = W \frac{(T_N - T_{MCL})}{(W_N - W_{MCL})} + T_{MCL} + 9,5(P - P_N) \quad (6)$$

A coolant temperature change in the reactor core leads to coolant density change, which affects the neutron moderation process and, accordingly, the reactor power. By changing the temperature in one direction or another, we can introduce both negative and positive reactivity.

However, in order to use temperature regulation as a sufficiently effective reactor power control action in load-following mode, it is necessary, firstly, to maximally increase the range of steam pressure variation in the second loop within the limits admissible for the reactor plant equipment. Secondly, it is necessary to abandon the maintenance of a rigid coolant temperature dependence at reactor power, providing the ability to promptly change the coolant temperature in order to introduce positive or negative reactivity into the reactor core as necessary. For NPP with VVER-1200, the range of steam pressure change in the second loop is theoretically $\pm 0,3$ MPa [9], and the rate of temperature change in the first loop is limited by the value $\Delta T/\Delta t = 10$ °C / h.

Note that, despite the expansion of the range of pressure variation in the reactor second loop to the specified limit $\Delta P = \pm 0,3$ MPa, during reactor operation, it is allowed to use a lower value $\Delta P = \pm 0,2$ MPa in order to maintain a margin up to the normal operation limits of NPP.

2.4 pressure in reactor secondary loop

VVER-1200 reactor operation in the basic mode is carried out maintaining a constant pressure in the second loop ($P = \text{const}$). At the same time, reactor power in load-following mode changes due to the joint operation of the turbine and reactor power regulators: the turbine regulator changes the turbine power at a given rate, the reactor regulator maintains the steam pressure in the permissible range ($P = P_N \pm \Delta P$) by corresponding power change. So, to reduce the reactor power, the turbine regulator partially closes the control valves, the turbine power decreases, the steam pressure increases. At the same time, while the steam pressure changes within the permissible range, the reactor power also decreases due to the self-regulation effect of the power unit: steam pressure increase in the secondary loop causes coolant temperature increase in the primary loop, which is accompanied by the introduction of negative reactivity and power decrease. The pressure change rate in the second loop $\Delta P/\Delta t = 0,04$ MPa / min.

The lag time for heat transfer between the second and the first loop is 10 s, which is due to the complete coolant circulation in the loop.

2.5 Reactor performance (efficiency) coefficient

When the NPP is operating, the electrical power grid requirements come in the form of a load bearing schedule. In order to execute this schedule, the thermal power released in the reactor core is controlled. The electric power generated by the turbine and the reactor thermal power is related as follows:

$$N_{GENERATOR} = W \cdot \frac{K_E(W)}{K_E(W_N)} \quad (7)$$

Where:

- $N_{GENERATOR}$: generator electrical power, %;
- W : current reactor power, %;
- $K_E(W)$: performance coefficient (efficiency) depending on the current reactor power W , %;
- $K_E(W_N)$: performance coefficient (efficiency) at nominal power ($W_N = 100\%$), %.

Calculation of VVER-1200 reactor performance coefficient dependence at the current power W (in percent at nominal power) will be carried out according to the formula obtained by constructing a polynomial approximation based on the experimental data of the sixth unit of the Novovoronezh NPP:

$$K_E(W) = 27,7716 + 0,00209505 \cdot W^2 - 0,000012711 \cdot W^3 \quad (8)$$

The reactor performance coefficient also depends on the ambient temperature and the vacuum parameters in the condenser, but this is not taken into account in formula (8).

2.6 Axial offset (AO)

The uniformity of energy release in the reactor core is indicated by the value of the axial offset (AO), which is defined as the difference between the powers of the upper (W_{Top}) and lower (W_{Bottom}) halves of the reactor core, relative to the total power:

$$AO = \frac{(W_{Top} - W_{Bottom})}{(W_{Top} + W_{Bottom})} \cdot 100\% \quad (9)$$

To facilitate operator reactor control and maintain field characteristics within acceptable limits, a power phase diagram has been developed, shown in figure 1, in the form of a family of hyperbolas, called phase trajectories [10].

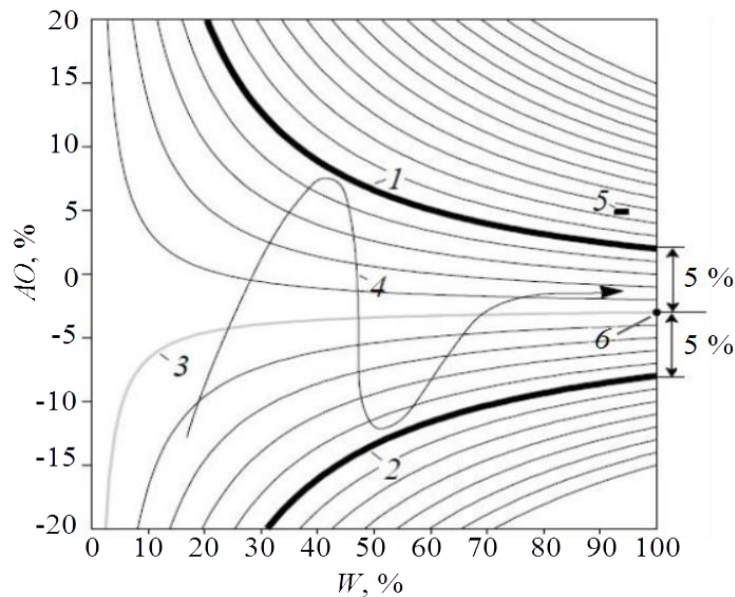


Figure 1. Offset-power phase diagram: 1, 2 - boundaries of the recommended area; 3, 4 —central and phase trajectories, respectively; 5 - predicted maximum offset; 6 - central offset at nominal power.

The offset power phase diagram is used to control the power released in the reactor core: Maintaining the current phase point in the recommended area of the diagram limits the change in local power and also inhibits the development of axial xenon oscillations. With a daily maneuver of power, the axial offset of power release in the reactor core may briefly go beyond the recommended range of the offset-power diagram. This is allowed for a single daily maneuver, but for repeated maneuvers, it is advisable to keep the offset within the recommended range, which will reduce the intensity of local power fluctuations, increase margins to maximum permissible values, and, in general, will contribute to an increase in the reactor operation reliability.

Provided that the reactor worked for a long time at constant power and with a stable offset, the central offset, the upper and lower boundaries of the recommended area are calculated using the formulas substantiated in work [11]:

$$AO_C = -2,6 + (AO_{ST} + 2,6)W_{ST} / W_N \quad (10)$$

$$AO_{Top} = -2,6 + (AO_C + 7,6)W_N / W \quad (11)$$

$$AO_{Bottom} = -2,6 + (AO_C - 2,4)W_N / W \quad (12)$$

Where:

- AO_C : central offset, corresponding to the central trajectory, %;
- AO_{ST} : stable offset (12 days of operation at constant power), %;
- AO_{Top} : upper corridor of allowed AO values, %;
- AO_{Bottom} : lower corridor of allowed AO values, %;
- W_{ST} : constant power for a long time of reactor operation, %;
- W : current reactor power, %;

Two phase trajectories, which form the upper and lower boundaries of the axial offset change, are at an equal distance from the “central trajectory”, which is the phase trajectory passing through the phase point corresponding to the long-term operation of the reactor. Boundaries of the offset-power phase diagram are determined by formulas (11) and (12), while at nominal power (100%), the boundaries of offset recommended area $AO_C = \pm 5\%$.

3. Imposed restrictions

The normal operation of a VVER-1200 reactor is carried out within the operational limits set by the reactor plant technical regulations. In addition to the operational limits of NPP normal operation, safe operation limits have been established, i.e. boundaries of parameter values of technological processes and control actions for controlling the reactor power, the violation of which can lead to accidents with damage to physical safety barriers. For example, the rate of reactor power change is limited: with increased power in the range from minimum controlled power level (MCL) to $45\% W_N$ and from 45% to $100\% W_N$, it should not exceed $3\% W_N / \text{min}$ and $1\% W_N / \text{min}$, respectively. When reactor power decreases in the range from 100% to MCL, it should not exceed $3\% W_N / \text{min}$. In the case where power increase after the long-term operation (more than two weeks) at any reduced level from $45\% W_N$, no more than $10\% W_N / \text{h}$, and from $80\% W_N$, no more than $1\% W_N / \text{h}$.

The main characteristics and control actions, which are constrained in the development of control algorithms for NPP with VVER-1200 are [12]:

- Linear load on the fuel element and, consequently, offset of energy release field;
- Coolant flow rate through the fuel assembly in the reactor core;
- Pressure in the reactor primary loop;
- Insertion position and speed of control rod groups;
- Speed of boric acid and distillate input-output;
- Limits of temperature change at the reactor inlet;
- Rate of temperature, pressure and power change.

All these restrictions must be introduced into the structure of the heuristic algorithm.

4. Heuristic approach

The heuristic approach is based on intuitive principles of solving a problem and is usually used when the optimal solution to a problem is unknown or when it is necessary to improve the operation of an existing system, for example, to solve an optimization problem using DPM.

In the dynamic programming method, the particular problem to solve is divided into stages, in our case temporary. For each stage, initial states are selected (for the first stage, let's call it start state). Then, sorting out possible controls, transitions are made to final states of the current stage. For each end state, the cost of arriving at it from start state is estimated. The end states of the current stage become start states for the next stage. If the final state does not pass through the constraints or some constraints are violated during the transition to it, then such a state is discarded. From the entire final states list of the last stage, the state with the lowest cost of arrival from the starting state is selected. For this state, moving backward through the stages, all controls are restored, they will be the optimal control.

The heuristic algorithm allows us to get a quick estimate of the transition cost from the starting state to the final one. Comparing the cost of arriving at the final state from the initial one with heuristic cost at each stage of DPM, one can say whether it makes sense to further consider this branch of transitions. If cost turns out to be greater than the heuristic, the branch is discarded, thereby significantly reducing further computational and memory costs. Whenever the heuristic algorithm is more efficient, the optimization based on DPM will work faster.

Papers [13-15] describe several practical manual control procedures, which were tested on mathematical models and real NPPs. The most common strategy is direct power offset control, which

forces power distribution to move towards the desired one under the control actions. This strategy is rather ineffective for suppressing xenon oscillations. Also, in these works are control strategies for load-following mode. Taking into account the experience of these works, a heuristic control algorithm was developed.

Let us consider in more detail heuristic algorithm for controlling the reactor power in load-following mode: 100% at nominal power (1 hour), 4 hours to decrease power to 50, %, maintaining power at 50% (6 hours), 4 hours to increase power to 100%, finally maintaining power at 100% (9 hours). The algorithm was used to control the reactor power over 15 daily cycles.

The heuristic algorithm includes three control actions: movement of control rod groups, boron and temperature regulation. The calculation functions take into account all the above restrictions. Heuristic algorithm stages are as follows:

- At the stages of maintaining and decreasing reactor power, temperature regulation dominates with the subsequent transition to control rod groups, and then with using water exchange. For each control, its own insensitivity range to the current reactor power deviation from the electrical grid load graph is selected. Namely, for primary loop temperature (0,1% at nominal power), for control rod groups (0,3% at nominal power) and for boric acid concentration (0,9% at nominal power). Control rod groups N°12 and N°11 moves only in the upper half of the reactor core in order not to greatly change the power of the core lower part and to try to keep the xenon distribution unchanged in it;
- At the stage of increasing power, insensitivity to current reactor power deviation from the electrical grid load graph for temperature and boron regulation is the same and equal to 0,1% at nominal power, control rod groups are used in case of lack efficiency of first and second controls (insensitivity range of the control rod groups is 0,9% at nominal power).

5. Results and discussion

Let us consider the results of the operation of various heuristic algorithms for the middle (170 eff. days) of the eighth fuel campaign of the sixth unit Novovoronezh NPP operating in load-following mode (100-50-100% at nominal power). When simulating reactor operation, the influence of fuel burnout was neglected. These following variants of heuristic algorithms were considered:

- without temperature regulation ($\Delta P = 0$ MPa);
- narrow range of temperature regulation ($\Delta P = \pm 0,05$ MPa);
- wide range of temperature regulation ($\Delta P = \pm 0,2$ MPa).

The results, shown in figure 2, indicate that during the first cycles of the electrical grid load graph (100-50-100% at nominal power), the VVER-1200 reactor parameters of control actions pass through several cycles of non-stationary changes until a steady state is reached, which is very noticeable on the graphs of boric acid concentration changes in the reactor.

For a more visual consideration of results, we will select four last steady-state cycles out of 15. The simulation results of these cycles are shown in figure 3, figure 4 and figure 5.

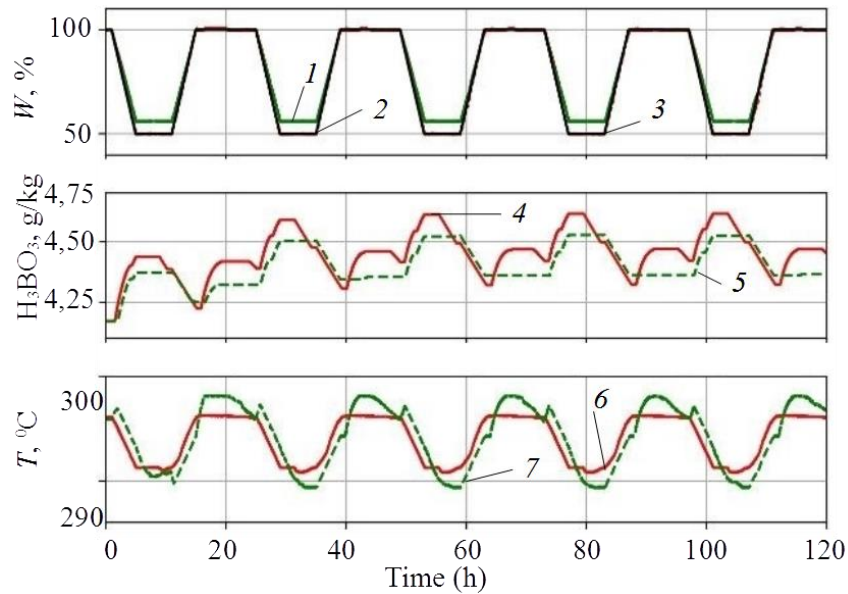


Figure 2. Transition to reactor steady-state during the first five operation days of the VVER-1200 reactor: 1 - core power; 2 - generator power; 3 - electrical grid load graph ($\Delta P = 0,2$ MPa); 4,5 - boric acid concentration ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively) ; 6,7 - temperature at reactor inlet ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively).

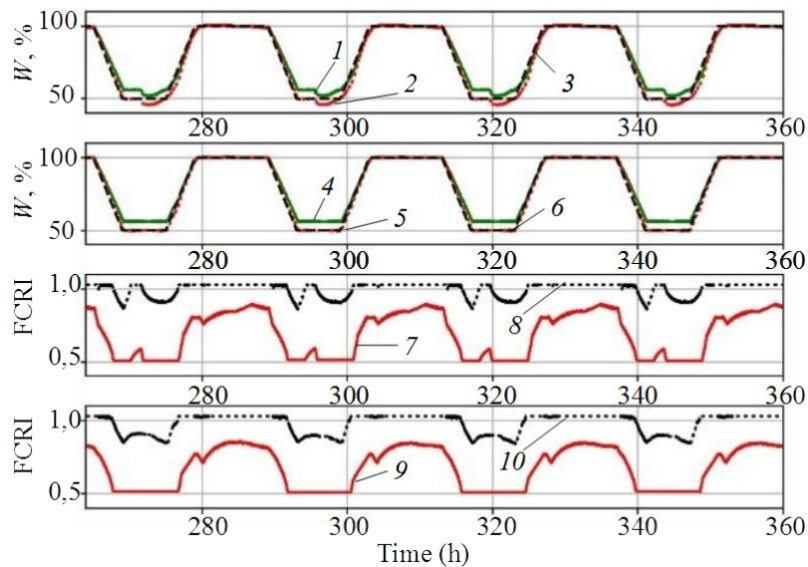


Figure 3. Main parameters in steady-state operation of the VVER-1200 reactor: 1 - core power ($\Delta P = 0$ MPa); 2 - generator power ($\Delta P = 0$ MPa) ; 3 - electrical grid load graph ; 4 - reactor core power ($\Delta P = 0,2$ MPa); 5 - generator power ($\Delta P = 0,2$ MPa); 6 - electrical grid load graph; 7 and 8 – fraction control rod insertion of group №12 and №11 ($\Delta P = 0$ MPa), respectively; 9 and 10 - fraction control rod insertion of group №12 and №11 ($\Delta P = 0,2$ MPa), respectively.

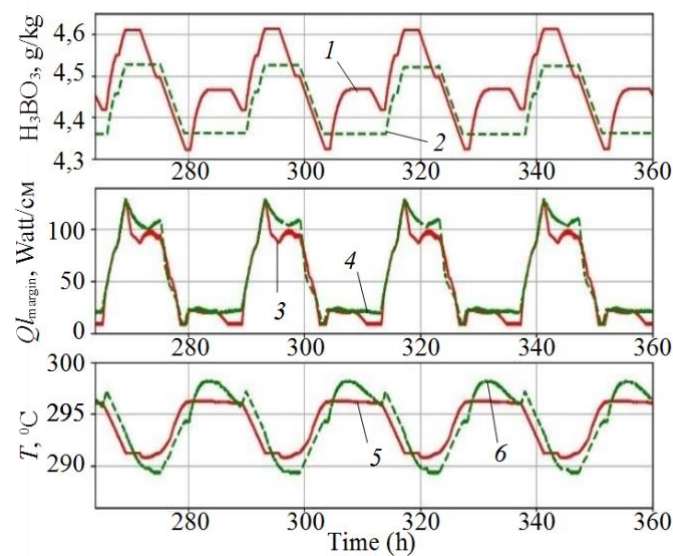


Figure 4. Main parameters in steady-state operation of the VVER-1200 reactor: 1,2 - boric acid concentration in the reactor ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively); 3,4 - margin for linear load ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively); 5,6 - temperature at reactor inlet ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively).

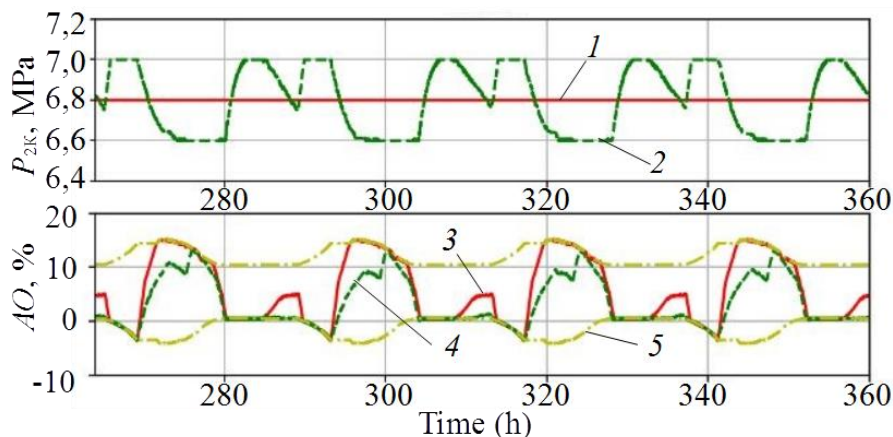


Figure 5. Main parameters in steady-state operation of the VVER-1200 reactor: 1,2 - pressure in reactor second loop ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively); 3,4 - axial offset ($\Delta P = 0$ MPa, $\Delta P = 0,2$ MPa, respectively); 5 - allowable limits of axial offset values.

Recall that in this work, a heuristic algorithm was developed to reduce the water exchange in the VVER-1200 reactor primary loop. Water exchange estimate results, presented in figure 6 and table 1, confirm the importance of using temperature controller with increased pressure range in the secondary loop: in addition to its contribution to the reactor power control, as explained, we obtained a decrease of water exchange by 24,6%, respectively, at $\Delta P = \pm 0,05$ MPa and by 50,36% at $\Delta P = \pm 0,2$ MPa in comparison to reactor power control without temperature regulation.

Using temperature regulation also allows for better compliance with the electrical grid load graph compared to the algorithm without temperature regulation.

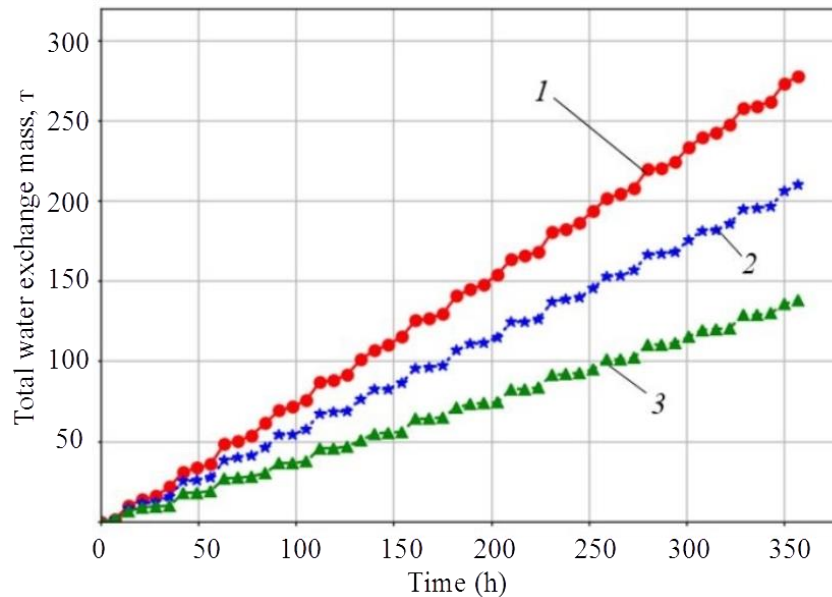


Figure 6. Total water exchange mass (Tonne) with different heuristic algorithm variants: 1 - without temperature regulation ($\Delta P = 0$ MPa); 2 – narrow temperature regulation range ($\Delta P = 0,05$ MPa); 3 – wide temperature regulation range ($\Delta P = 0,2$ MPa).

Table 1. Comparison of water exchange values for different heuristic algorithm variants.

Established cycles and 15 days total	Water exchange mass (Tonne)			Water exchange reduction	
	Variant 1 ($\Delta P = 0$ MPa)	Variant 2 ($\Delta P = 0,05$ MPa)	Variant 3 ($\Delta P = 0,2$ MPa)	Variant 1 — Variant 2	Variant 1 — Variant 3
For the 15th day, T	18,98	14,33	9,27	4,65	9,71
For the 15th day, %				24,52	51,15
For 15 days, T	278,71	210,16	138,32	68,55	140,38
For 15 days, %				24,60	50,36

Note: Variant 1 - without temperature regulation; variant 2 - narrow temperature regulation range; variant 3 - wide temperature regulation range.

6. Conclusion

To solve the minimizing water exchange problem in the VVER-1200 reactor primary loop operating in load-following mode a DPM was chosen. However, this method is very expensive in terms of the amount of RAM and the time it takes to carry out calculations. In order to reduce the computational costs during the operation of the algorithm based on the DPM, it is proposed to use a heuristic algorithm for cutting off ineffective branches in the DPM. The use of temperature control in heuristic algorithm made it possible to reduce the amount of liquid removed from the reactor primary loop, namely, for a narrow temperature regulation range, water exchange decreased by 24,6%, for a wide temperature regulation range, water exchange decreased by 50,36% compared to reactor power control without temperature regulation.

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