ТЕХНОЛОГІЇ ТА ОБЛАДНАННЯ В ЕНЕРГЕТИЦІ

TECHNOLOGIES AND EQUIPMENT IN ENERGY

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OPTIMIZATION OF POWER LOAD FOLLOWING MODES FOR VVER-1000

The need to involve nuclear power plants in daily power regulation is driven by the gradual increase in the share of renewable energy sources in the Unified Energy System (UES) of Ukraine. Additionally, the conditions for implementing measures to address climate change and deteriorating operating conditions of the UES in the face of economic changes play a significant role. There is an increased demand for maneuverable capacity to ensure the fulfillment of the daily electricity consumption schedule. However, the existing daily power regulation mode for PWR-1000 in Ukraine has significant drawbacks.

Therefore, this paper proposes a method for optimizing the daily power regulation mode, examines the shortcomings of the existing power regulation method at nuclear power plants with PWR-1000 reactors in Ukraine, and suggests an approach for their elimination — utilizing the so-called "grey" rod clusters for power load following in this mode.

Keywords: *VVER-1000, power maneuvering, daily power regulation, "grey" rod clusters, DYN3D.*

Testing the Maneuverability of VVER-1000 (KhNPP-2)

Let's take a closer look at the mode of daily power regulation, which involves unloading-loading of the VVER-1000 nuclear power plant unit according to a clear algorithm, within a strict range and at a rate of change of the reactor power (established by the technological regulation of safe operation). It is important to ensure strict control over compliance with the parameters of the power unit operation in accordance with the requirements of nuclear and radiation safety norms and rules.

So far, the implementation of the daily power regulation mode for the active zone, fully formed with TVZA (thermal dissipation assembly of alternative designs), is underway at the second unit of the Khmelnytsky Nuclear Power Plant. During the second fuel campaign in 2006, experimental tests of the daily power regulation mode were successfully conducted for two moments of the fuel campaign (at the beginning of the fuel campaign - starting from the 106th effective day and in the middle of it - starting from the 175th effective day). Additionally, experimental operation of the daily power regulation mode for the second unit of the Khmelnytsky Nuclear Power Plant was carried out in the tenth fuel campaign.

As a result of these tests, violations of the limits and conditions of safe operation of the power unit were recorded, but certain measures were implemented, and at the final stage of testing, a stable state of the reactor unit was achieved. Thus, the presented capability ensures the parameters of the active zone and fuel in transient modes within limits that do not lead to fuel cladding failure due to the occurrence of fuel sheath defects.

The main control problems in the energy release field during power load following modes in VVER-1000 reactors are the damping of xenon oscillations and control of axial offset throughout the active zone.

Considering the results of many studies conducted at the second unit of the Khmelnytsky Nuclear Power Plant, the most expedient ones were found to be the investigation of the power load following mode using mechanical control devices and boron control systems without using the central control element of the CPS, as well as the study using the central control element of the CPS in the power load following mode of the power unit.

Based on the results of these studies, taking into account all the advantages and disadvantages of these two methods, especially the safer operation and minimal axial offset fluctuations with the first method, the first stage of experimental operation of the daily power regulation mode at the nuclear power plant was carried out precisely using the method without the central control element of the CPS. The change in the main parameters during the experimental operation of the daily power regulation mode for the second unit of the Khmelnytsky Nuclear Power Plant in the tenth fuel campaign is shown in Fig. 1 [1-2].

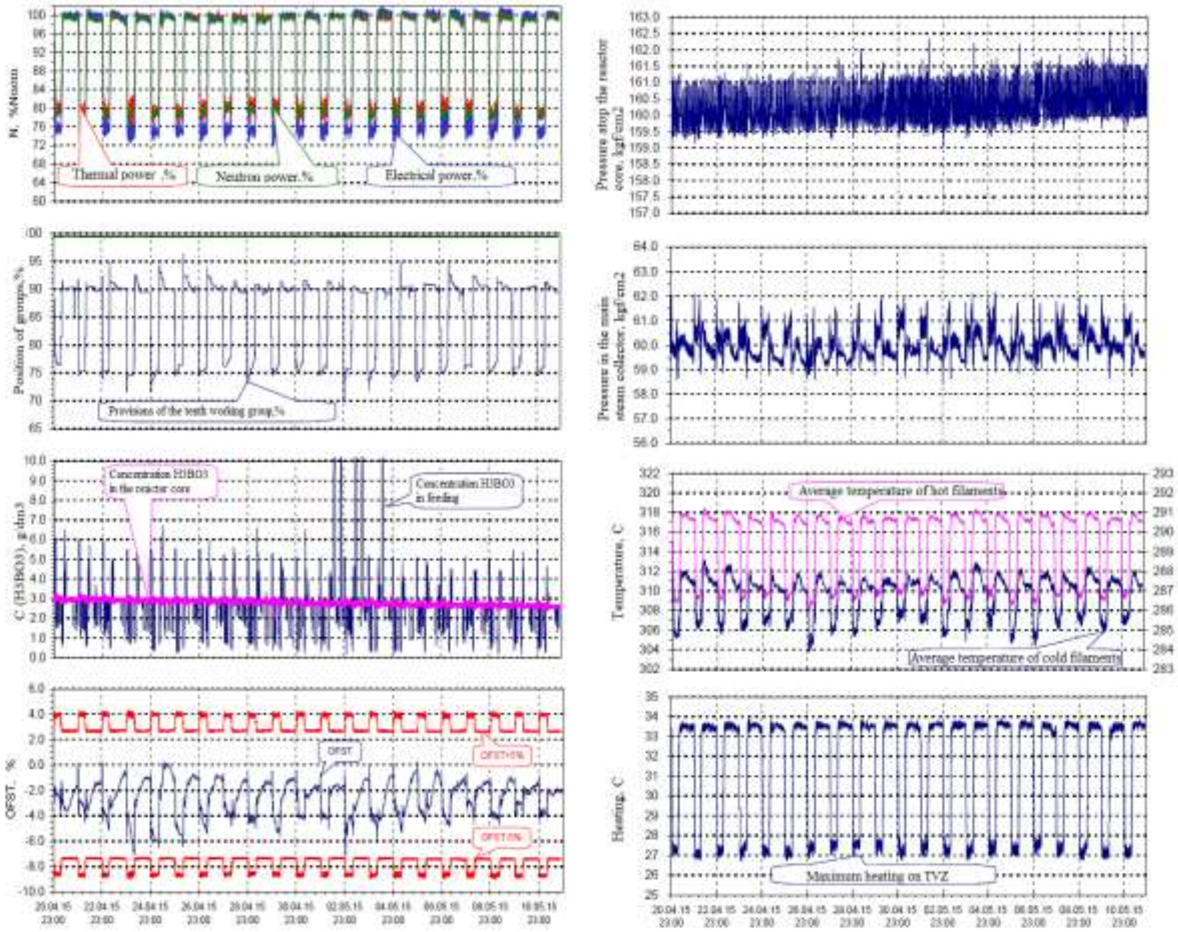

Figure 1 - *Change in main parameters during experimental operation of the daily power regulation mode for the second unit of the Khmelnytsky Nuclear Power Plant in the tenth fuel campaign.*

During the experimental operation of the daily power regulation mode throughout the tenth fuel campaign, drawbacks and recommendations were identified, based on which the following measures are recommended:

1) Increase the level of automation of the daily power regulation mode. Despite the fact that the automatic power regulator during daily power regulation was in automatic mode, its operation was essentially protective. The automatic power regulator operated if the personnel could not (did not have time to) make adjustments to the pressure settings in the main steam header and/or influence the control elements of the CPS. The extensive actions of the operating personnel increase the risk of making mistakes.

2) The appearance of the WP-2 (warning protection) signal during the introduction of distillate limits the optimization of load execution in both automatic and manual modes. The algorithm for generating the WP-2 signal does not take into account either the coolant flow rate or the speed and magnitude of reactivity introduction during the group rise. This leads to restrictions on controlling the reactor power at rates of positive reactivity introduction significantly lower than the speed achieved by one of these methods when maximizing the design capabilities.

3) Increasing or decreasing the reactor power involves introducing a solution of boric acid or distillate into the primary circuit. For the operator to strictly adhere to the program during the introduction of the mentioned media, it is necessary to keep track of seconds, and this approach does not exclude the possibility of inaccuracies in determining the total time of media introduction.

4) For nuclear power plant units in Ukraine with feed pumps having clearance seals, when choosing the duration of portions of boric acid solution, it is necessary to take into account that the delay in the arrival of part of the distillate will be up to 40-50 minutes. This is due to the significant flow rate through clearance seals (up to 12 m3/h per three units). The introduction of boron will also have a similar effect but smaller.

5) Compared to the base mode, the operation of the power unit in the daily power regulation mode increases the number of actions (often repetitive) of the operating personnel on the control panel many times, increasing the likelihood of errors.

Most of the mentioned drawbacks can be eliminated by abandoning boron regulation, only through regulation using the mechanical control system of the CPS, in particular, the problem of the WP-2 signal that imposes a ban on introducing reactivity by two means to prevent violations of nuclear safety rules.

Thus, reactivity control during maneuvering can be implemented either through boron regulation or using the control elements of the CPS. Analyzing the advantages and disadvantages of the two methods, the method of regulation using the control elements of the CPS, namely using "gray" rod clusters, proved to be more expedient in my opinion.

As a result of abandoning liquid regulation, there will be a problem of increasing the efficiency of the control elements of the CPS, which can be solved by increasing the immersion depth of the control elements of the CPS. However, such immersion of clusters increases the deformation of the energy release field and will also cause xenon oscillations. Thus, "gray" rod clusters may be a better alternative as they will increase the efficiency of the control elements through immersion depth but will not cause significant deformation of the energy release field and xenon oscillations. The implementation of "gray" CPSs in this work will be achieved by changing the number of clusters in the control elements of the CPS. In standard CPSs, there are 18 clusters, and in this work, two options for implementing "gray" CPSs are demonstrated:

- CPS with 12 clusters
- CPS with 6 clusters

Calculation of the thermal dissipation assembly model in WIMS with varying numbers of absorbing rods.

WIMS is a comprehensive reactor lattice code that allows, based on neutron transport theory, the calculation of neutron flux as a function of energy and position in the lattice. The calculation scheme of the WIMS code is based on solving the neutron transport equation using the probability method of the first collision, enabling the calculation of neutron flux distribution depending on energy and position in the grids.

A distinctive feature of my approach to modeling the thermal dissipation assembly of a VVER using the WIMS program is the conformal transformation of the hexagonal shape of the thermal dissipation assembly into a circular shape, as depicted in Fig. 2

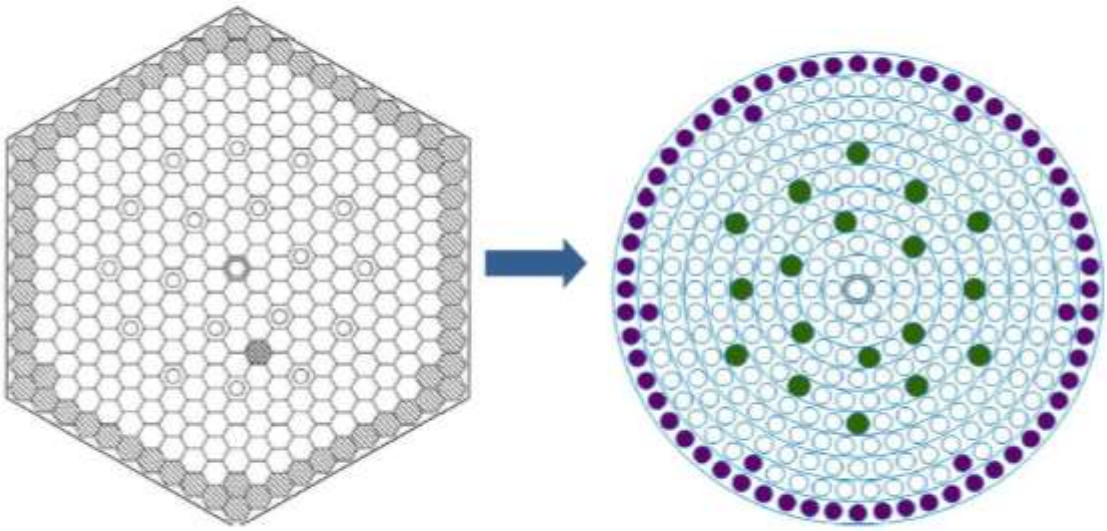

Figure 2 - *Computational model of the thermal dissipation assembly of the VVER-1000 implemented in WIMS.*

With the specified parameters, the computational model of the thermal dissipation assembly with different numbers of absorbing rods (with fewer absorbing rods - gray rod clusters) can be depicted, resulting in some differences. Such computational models of thermal dissipation assemblies in two variants (with 12 and 6 clusters) are shown in Fig. 3.

The obtained results of calculations on the influence of the number of absorbing rods in the cluster on K_∞ are depicted in Fig. 4.

The performed calculations show that the number of absorbing rods affects the change in K_∞ in the TVZA with an immersed cluster. With the standard number of absorbing rods, it equals 0.35, while with 12 absorbing rods it is 0.25, and with 6 absorbing rods it is 0.15.

The obtained results were further used to prepare a library of neutron-physical constants in the DYN3D program and for the calculation of daily power regulation modes with the proposed variants of gray clusters.

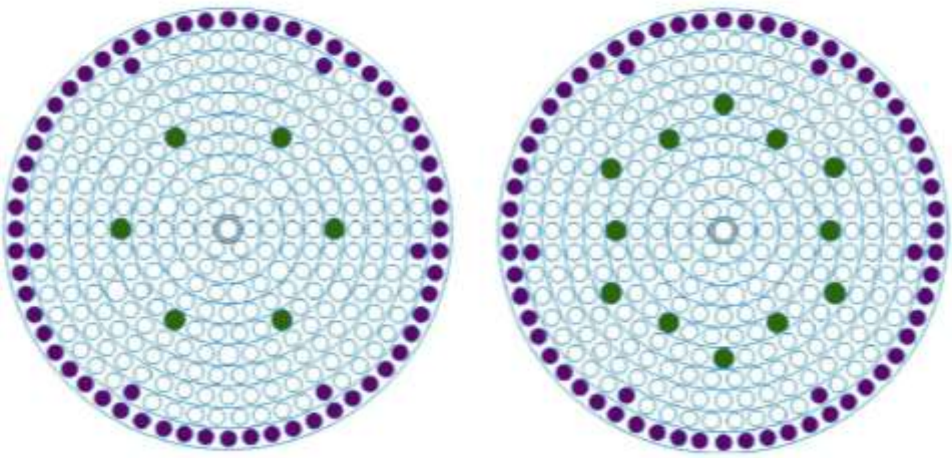

Figure 3 - *Model of the thermal dissipation assembly of the VVER-1000 in WIMS for six and twelve absorbing rods.*

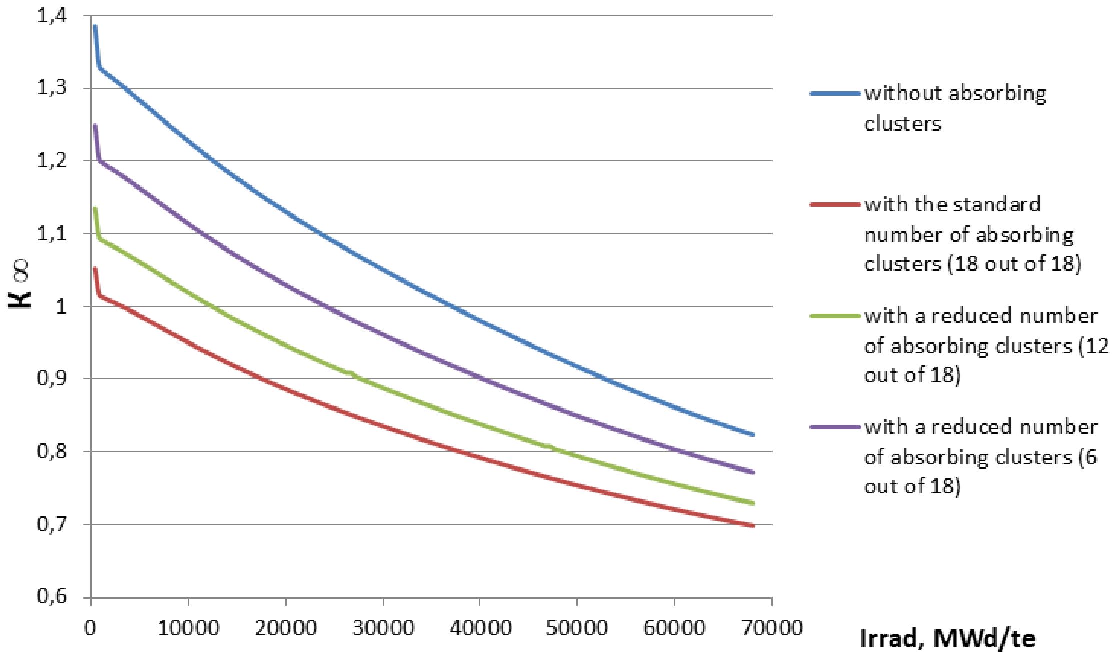

Figure 4 - *Influence of the number of absorbing rods in the cluster on K∞*

Calculation of daily power regulation modes in VVER-1000 reactors with gray control and protection system (CPS) in the DYN3D program.

The three-dimensional code DYN3D is widely used for calculating stationary states and transient processes in light-water reactors with hexagonal layouts of thermal dissipation assemblies, such as VVER. The capability to calculate time-dependent power distribution is implemented in the code using the internal power reconstruction method. For the validation of the power distribution calculation module in the DYN3D program, a constant library was developed [3].

Control of groups of control and protection system (CPS) elements in the mechanical control system was carried out based on the need to:

- Ensure minimal (permissible) deformation of the axial power distribution (offset);
- Adhere to conditions regarding minimum values of power distribution non-uniformity coefficients and linear power loads;
- Adhere to the permissible rate of reactor power change set in the Technical Specifications for Reactor Operation (TSRO);

- Take into account the accuracy of maintaining reactor parameters during the transient process (offset, power) and the acceptability of the rates of change in boric acid concentration and movement of CPS elements from the perspective of the functioning of the reactor facility's technological systems and equipment.

Let's consider the results of the computational modeling of this transient operation mode of the VVER-1000 while adhering to the daily load schedule in the power system, as depicted in Fig. 5.

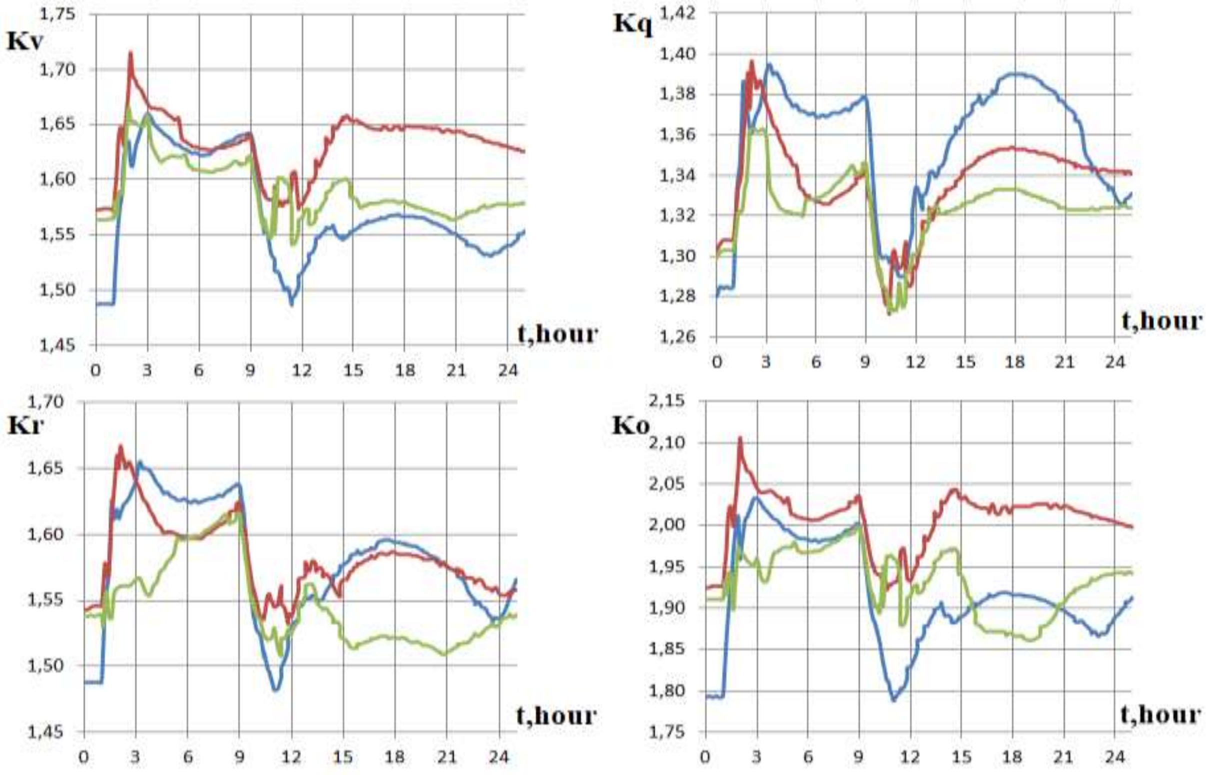

Figure 5 - *Change in power distribution non-uniformity coefficients (Kq, Kv, Kr, Ko)*

Explanation of the graphs:

- Red graphs represent the daily power regulation mode with the CPS 18 arrangement with 18 clusters and without boric acid regulation.
- Blue graphs represent the daily power regulation mode with the CPS 12 arrangement with 18 clusters and without boric acid regulation.
- Green graphs represent the daily power regulation mode with the CPS 6 arrangement with 18 clusters and without boric acid regulation.

Kq - radial non-uniformity coefficient for thermal dissipation assemblies.

Kv - volumetric non-uniformity coefficient for thermal dissipation assemblies.

Kr - radial non-uniformity coefficient for thermal dissipation elements.

Ko - volumetric non-uniformity coefficient for thermal dissipation elements.

In order to implement power reduction during the daily power regulation mode, only one control element was used in 5 groups in the standard arrangement of the control and protection system (CPS) components (18 out of 18 clusters). In the variations with the implementation of "grey" CPS with 12 or 6 clusters out of 18, two control elements were used (in opposite sectors of the active zone) in 5 or 6 groups. This number of "grey" CPS, on the one hand, ensures the execution of power maneuvers with minimal deformation of the energy release field, and, on the other hand, in the event of reactor emergency protection actuation, the number of control elements in the groups ensures the necessary subcriticality of the reactor.

Considering one of the important issues in the experimental operation of the l mode at the second unit of the Khmelnytskyi Nuclear Power Plant – the control of axial offset oscillations within permissible limits (±5%), the calculated modes kept the change in axial offset within ±1.5%, which can be considered insignificant oscillations within permissible limits for power maneuvers.

From the graphs, it can be concluded that the method using CPS with only 6 clusters induces the least deformation of the energy release field in the VVER-1000 reactor during the daily power regulation mode. However, to achieve power changes with "grey"rod clusters, more activated groups and deeper immersion of the CPS rods into the active zone are required. This may have a negative impact on further operation in the event of emergency protection system actuation.

Conclusions

Based on the results of the experimental operation of the daily power regulation mode at the second unit of the Khmelnytskyi Nuclear Power Plant in the tenth fuel company, taking into account all the drawbacks and advantages, as well as the obtained results of calculations in the DYN3D program, an optimization method for the daily power regulation mode is proposed. The proposed method involves the use of "grey" control and protection systems (CPS) with the abandonment of boron regulation in this mode. The obtained calculation results demonstrate the fundamental feasibility of using "grey" CPS in this mode. Among the considered options for implementing "grey" CPS, the most optimal is the arrangement with 12 out of 18 clusters in the CPS rods. This arrangement induces minimal deformation of the energy release field, ensures the maintenance of axial offset within permissible limits, and minimally affects the effectiveness of emergency protection during power maneuvers.

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ОПТИМІЗАЦІЯ РЕЖИМУ МАНЕВРУВАННЯ ПОТУЖНОСТІ ВВЕР-1000

Необхідність залучення атомних електростанцій в роботу в режимі добового регулювання потужності зумовлена поступовим зростанням частки відновлювальних джерел енергії в Об'єднаній енергетичній системі України. Також значну роль відіграють умови для впровадження заходів щодо запобігання змінам клімату та погіршення умов функціонування ОЕС України в умовах зміни економічної ситуації: збільшення потреби в маневреній потужності для забезпечення виконання добового графіку споживання електроенергії, але існуючий режим добового регулювання потужності на ВВЕР-1000 в Україні має вагомі недоліки

Тому в даній роботі запропоновано метод оптимізації режиму добового регулювання потужності, розглянуто недолікі існуючого методу регулювання потужності на атомних електростанціях з реакторної установкою ВВЕР-1000 в Україні і запронувати підхід для їх усунення –використання для маневрування потужності в даному режимі так звані ”сірі” кластери .

Ключові слова: *ВВЕР-1000, маневрування потужності, добове регулювання потужності,”сірі”кластери.*

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