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Research of WWER-1000 Power Change Modes for Operation in the Load-Following Mode

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Ukrainian nuclear power plants (NPPs) generate approximately 55 % of all the country's electricity production in the basic mode. The Ukrainian energy system faces power shortage for load-following mode (LFM). Hence, it is advisable to consider possibility to opperate Ukrainian NPPs in LFM. The second stage of LFM pilot operation has been completed at Khmelnitsky NPP Unit 2 to date.

Following the above, the research of LFM implementation key aspects at Ukrainian NPPs is urgent and relevant. One of the key aspects is the definition of the appropriate mode for reactor power change in LFM for common type of the Ukrainian reactors (WWER-1000/V-320).

Power density field and thermal power in WWER-1000 are controlled by means of boron control and control rods. The paper provides investigation of the standard power change modes and power density field control in accordance with the safety requirements in the context of the boric acid volume used to decrease the power level, the axial offset stability, maximum values of the power peaking factor and fuel utilization performance (parameters).

The computer data of the parameters are obtained in SE «NNEGC «Energoatom» during neutron-physical calculations of WWER-1000 cores by means of the «BIPR-7A» program, that uses a mathematical model of WWER reactors. The calculation was conducted for three modes:

Mode 1: CRs of group 10 and boron control. The mode is being operated for LFM in Ukraine. Group 10 and boric acid/distillate water (BC) are used for power change and power density field control.

Mode 2: Only CRs of group 10. Only group 10 is used for power change and power density field control.

Mode 3: Only CRs of groups 10, 9 and 8. All the A-algorithm control groups are used for power change and power density field control.

Compensation of the slow reactivity variations due to the xenon poisoning and fuel burn up before/after power change was provided by boric acid for all modes.

The research define the appropriate mode in the context of the parameters.

The research determine the advantages and drawbacks of the considered modes in the context of the parameters, as well as ways to improve the power density field control and power change system of WWER-1000 core.

Keywords: WWER-1000, load-following mode, boron control, axial offset, Kq, fuel utilization performance.

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Introduction

A load following power plant is a power plant that adjusts its power output as demand for electricity fluctuates throughout the day [1]. NPPs are usually operated as a base-load source of electricity. The main reason is that operating an NPP at rated power is usually more economically and simpler. The share of nuclear power in the most countries' energy mixes is small, thus, there is no need to operate them in LFM.

However, the situation is different in several countries. The share of nuclear power in the national energy mix of some of them had become so important (e.g., France and Ukraine), that the nuclear operators had to implement or improve the load-following capabilities at their NPPs.

Ukrainian NPPs currently generate approximately 55 % of all the country electricity production in the basic mode. Nuclear power generation in Ukraine is based on the WWER reactors (water-cooled and water-moderated power reactor). WWER-1000 (V-320) is common type of the reactors in Ukraine (11 from 15).

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The hydro power plants (HPP) in the Ukrainian energy system are operated in LFM, and the thermal power plants (TPP) are operated to meet the power demand, which HPPs cannot satisfy. The Ukrainian TPPs are characterized by high-cost electricity generation, high level of equipment deterioration and environmental stress [2]. The energy system in the current political and economic situation faces the power shortage for LFM. Hence, it is advisable to consider possibility to opperate Ukrainian NPPs in LFM.

Following the above, the research of the key aspects in LFM implementation at Ukrainian NPPs is urgent and actual. One of the key aspects is definition of the optimum reactor power change mode for LFM for the common type reactors in Ukraine.

Listing

A	coefficient of conversion, %
B	fuel assembly burn up, MWt·day/kgU
C	boric acid concentration, k^g/m^3
E	fuel assembly energy potential, MWt/day
H	position of CR group, %
Kq	power peaking factor
N	reactor thermal power, MWt
T	efficient time of reactor operation, efficient day
U	uranium with natural enrichment
V	volume, m^3
c	U-235 allowance in natural uranium (0.7 %)
t	time, h
x	average enrichment of fuel assemblies in the core, %
y	U-235 allowance in enrichment facility waste (0.3 %)
	Greek letters
γ	average burn up in unloaded fuel assemblies, MWt·day/kgU
ρ	density, $^kg/m^3$
	Subscripts
a	boric acid
ac	acceptable
b	in the beginning of the campaign
c	current
e	in the end of the campaign
f	finite
i	number of cycles of power variations during a fuel campaign
in	initial
k	number of fuel assemblies in the core
o	new fuel assembly
p	the primary system
r	regulate
rt	rated

Analysis of Published Data and Problem Definition

The Swedish, Finnish, France and German experience of LFM implementation in the light water reactors was analyzed [3] – [6], as well as the requirements for LFM [7], [8]. Some reactors in France and Germany are being currently operated in the load-following mode with large daily power variations of about 50 % of rated power. The change of the reactors' power level could be performed by control rod movement and by changing the boric acid concentration (neutron absorber) in the primary coolant. [9] The same approaches are used to control power density field and thermal power in WWER-1000/V-320 reactors.

LFM tests and experiments at WWER reactors have been performed since 1980. For example, an operation mode with sinusoidal power changes (with a period of 20-30 h) was tested in the early 1980s with WWER-440 reactors in Germany (Reinsberg and Greifswald NPPs) [9]. To date, the second stage of the pilot operation (21 cycles of power change) of WWER-1000 LFM has been completed at Khmelnitsky NPP unit 2 [10]. In addition, the experience of the maneuverability of a recent WWER design was analyzed considering the Russian AES-2006 Project with WWER-1200 [11], [12].

One of the key aspects for all the types of light water reactors is definition of the optimum mode of reactor power change for LFM. Several important physical effects limit the possibilities of power variations in a light water nuclear reactor such as WWER:

counter-reactions: moderator effect (change in primary coolant temperature), Doppler Effect (change in fuel temperature) and change in the axial distribution of coolant temperature in the core;

fuel burnup: boron concentration decreases with time, thus, boron concentration is almost equal to zero at the end of the fuel cycle, and the control rods are in the upper position;

fission product poisoning: change in reactor power causes the transient process of xenon oscillation with a change in the total number of 135Xe nucleus in the core and the corresponding change of reactivity.

Following the reactor operating requirements (the safety analysis report and technical specifications for operation), several modes/approaches could be used for the control in the power density field and thermal power in the core operated with four-year fuel campaigns for power changes.

Hence, the main issue for definition of the optimum power change mode for LFM is the most effective approach to control power density field and thermal power in the reactor. Another important issue is the analysis of additional costs to operate the mode based on the approach.

WWER-1000 reactors are not being operated in LFM. In that case, publications of the topic are focused on analyzing the possibilities to operate them in this mode and/or their maneuvering capabilities [11], [12]. Some publications analyze specific approaches to improve the effectiveness of the balance in the primary and the secondary loops [13] – [16]. The publications do not include combined analyzes and research of the modes.

The modes could be analyzed in accordance with the safety requirements in the context of the boric acid volume used to decrease the power level, the axial and radial offset stability and the fuel utilization performance (the parameters).

Power Density Field and Thermal Power Control

Power density field and thermal power in WWER-1000/V-320 are controlled by BC and CRs.

BC in the reactor is not automatized for LFM and is a major component of some radioactive waste streams arising at NPPs and, as long as it is present, it dominates the chemistry of the waste streams. The approach used to deal with boric acid in radioactive waste streams is particularly important and has significant financial, technical and environmental impact [17].

Nevertheless, it is still very popular. The analyzed approaches [10] – [16] consider BC for power drop and power density control during LFM. Boron control does not cause local power peaking and impact on the power density field is predictable.

Advanced algorithms to control power density in the core (A-algorithms) were implemented in the in-core control system at Ukrainian NPPs in the context of improving effectiveness of power and xenon oscillation control with minimum water exchange. The feature of A-algorithms is a new approach to CR application and implementation of the new module of information support. Three CR groups (No. 10, 9 and 8) in A-algorithms are operated to control the core (Figure 1). Group 10 (6 control banks) is partially positioned in the core all the time. Groups 9 (7 control banks) and 8 (9 control banks) can be inserted into the core during reactor unloading and/or suppression of xenon oscillations [18].

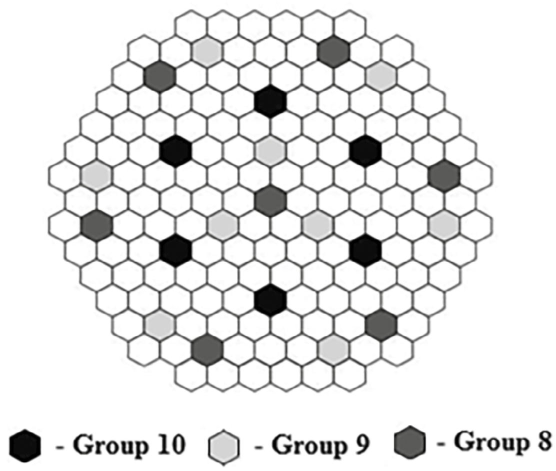

Figure 1 – Location of control groups for A-algorithms

Calculation of Power change Modes for LFM

Calculation was made for three modes with standard operation procedures.

Mode 1: CRs of group 10 and boron control. The mode is being operated for LFM in Ukraine. Group 10 and boric acid/distillate water (BC) are used for power change and power density field control.

Mode 2: Only CRs of group 10. Only group 10 is used for power change and power density field control.

Mode 3: Only CRs of groups 10, 9 and 8. All the A-algorithm control groups are used for power change and power density field control.

Compensation of slow reactivity variations due to xenon poisoning and fuel burnup before/after power change was provided by boric acid for all modes.

The calculation data of the parameters are obtained in SE «NNEGC «Energoatom» during neutron-physical calculations of WWER-1000 cores by the «BIPR-7A» program, that uses mathematical model of WWER reactors. «BIPR-7A» is a program from the «KASKAD» calculation complex. The BIPR-7A uses a three-dimensional mathematic model of WWER reactors and provides neutron-physical characteristics of the core. It simulates the core state during burnup, xenon oscillation in accordance with the parameters such as CR positions, power level, temperature etc.

The BIPR-7A neutron-physical model is similar to the «Imitator reactora» program. The «Imitator reactora» program was operated in the core control system software at unit 2 of the Hmelnytska NPP for the LFM [10]. The program was developed for fuel cycles and reactor control algorithms improvement in the design and scientific calculations, as well as information support tool of the reactor operator [19].

Requirements for LFM at Ukrainian NPPs are set in accordance to the safety analysis report [20]. The calculation was performed in accordance with the following requirements:

not over 200 cycles of power variations during a fuel campaign;

power variation between 80 % and 100 % Nrt per cycle;

compliance with the AO and Kq requirements (320.00.00.00.000.D61 Part 42.11).

LFM starts from the 5th effective day (96th hour) from the beginning of the campaign. Load following

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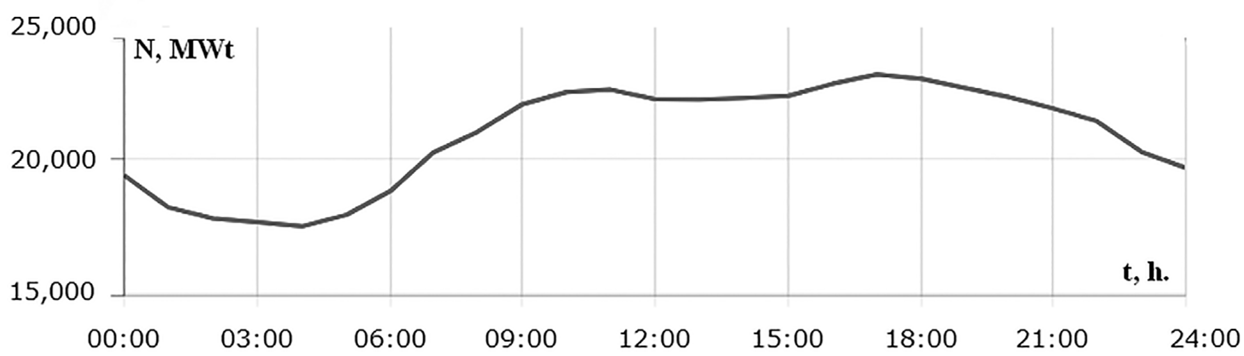

Figure 2 – Energy consumption in Ukraine as of 29 November 2018

during the calculation in accordance with energy consumption in Ukraine during a day (Figure 2):

power drop from 100 to 80 % N_{rt} (75 % of electric power) with acceptable speed during an hour;

operation at a power level of 80 % N_{rt} during 7 hours;

power increase from 80 to 100 % N_{rt} with acceptable speed during 2 hours;

operation at a power level of 100 % N_{rt} during 14 hours.

Calculation was made for WWER-1000/V-320 reactor loaded by FA-A fuel produced by the TVEL Fuel Company. Fuel campaign was made in accordance with the nuclear operator's standard [21].

Calculation of the Parameters

The boric acid volume used to decrease power level. The boric acid volume used to decrease power level was calculated according to the formula [22]:

$$V_m = \sum_{i=1}^{200}\left(-V_p \cdot \frac{\rho_p}{\rho_m} \cdot \ln\frac{C_i^f - C_m}{C_i^{in} - C_m}\right),\ m^3, \quad (1)$$

where: v_p= 372 m[3], ρ_p= 727 kg/m[3], ρ_m= 1000 kg/m[3] and c_m= 16 kg/m[3].

The boric acid volume for compensation of the slow reactivity variations due to the xenon poisoning and fuel burnup has not been considered.

The axial offset stability. Various safety constraints on the maximal local fuel heating rate (with regard to different accidental scenarios like LOCA) determine the operational domain depending on the reactor power and the AO [9]. The AO corresponds to the current xenon allocation. Therefore, the AO stability characterizes possibility to avoid the xenon oscillations and local power peaking.

In the paper, the AO stability was characterized by indicative index – the instantaneous axial offset (IAO) variation. IAO characterizes the power density field relation of upper and lower part of the core and corresponds to the current xenon allocation. The IAO variations is the ratio between the instantaneous axial offset in the beginning and in the end of the power reduction.

AO restrictions are provided in the form of the offset-power diagram (Figure 3) that demonstrates an optimum process path and boundaries of the acceptable area. The diagram is a part of the module of information support in the in-core control system [18].

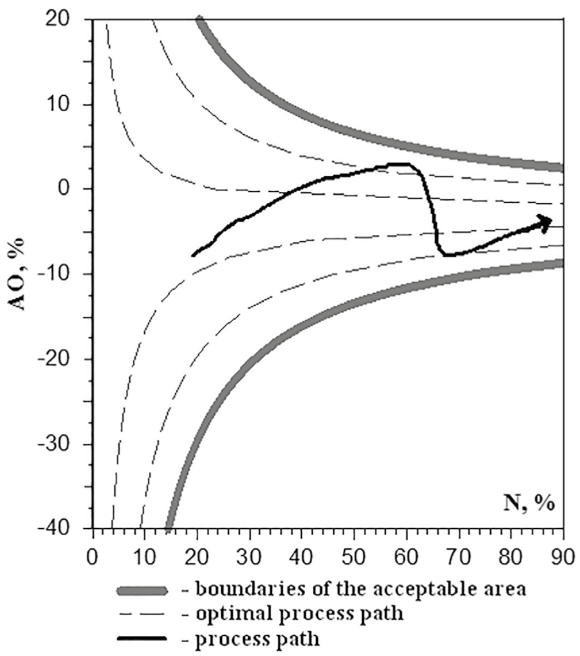

Figure 3 – AO-power diagram for A-algorithms

The axial offset stability was calculated for LFM third and 101st cycles.

The maximum values of the power peaking factor. Kq provides limitation for FA local power in the core [18]. Hence, Kq maximum value was chosen as a parameter that characterizes maximum radial deformation of the power density.

Kq is a relation of power in FA and average power of all FAs in the core. Kq characterizes maximum radial deformation of the power density. Kq_{ac}=1.35 is an acceptable value for Kq at rated thermal power of the reactor (3000 MWt). If Nc<Nrt Kqac is calculated according to the formula (320.00.00.00.000.D61 Part 42.11):

$$Kq_{ac} = \frac{1{,}35}{(0{,}83 \cdot N_c / N_{rt} + 0{,}17)}. \quad (2)$$

Kq was characterized in the paper by a maximum value during the fuel campaign.

The fuel utilization performance. The fuel utilization performance (FUP) is a technical-and-economic parameter, which characterizes the efficiency of the fuel utilization for thermal energy production in the core. FUP in the paper is based on the calculated parameters, which are described in the calculation methodology of the Ukrainian nuclear operator: the coefficient of the fuel energy potential utilization (FEPU) and the natural uranium rate (NUR) [23].

The FEPU is a dimensionless coefficient that is a ratio of produced thermal energy in the core to the energetic potential of operating fuel assemblies (FA) during the fuel campaign. The energetic potential of FA is thermal energy, which FA can produce during operation in achieving the regulated burnup. The FEPU is calculated according to the formula [23]:

$$FEPU = \frac{T \cdot N_{rt}}{E_b - E_e}, \quad (3)$$

where:

$$E_b = \sum_{k=1}^{163} (E^o{}_k \cdot (1 - \frac{B_{b.k}}{B^r{}_k})^2), \quad (4)$$

$$E_e = \sum_{k=1}^{163} (E^o{}_k \cdot (1 - \frac{B_{e.k}}{B^r{}_k})^2). \quad (5)$$

The NUR is the natural uranium rate for producing thermal energy in the core. The NUR is calculated according to the formula [23]:

$$NUR = \frac{A}{\gamma}, kg\,U_n / MWt \cdot day, \quad (6)$$

where:

$$A = \frac{x - y}{c - y}. \quad (7)$$

The comparison of the modes is based on the coefficients of FEPU decrease and NUR increase. Those coefficients were calculated as the ratio of the fuel utilization parameters in LFM to those parameters in the basic mode.

Calculation

The Table 1 provides the calculation results of the parameters. These results define that there are no significant differences between the modes and the basic mode in terms of FUP. All the modes are characterized by acceptable Kq values during the fuel campaign. Hence, it is advisable to consider the modes in the context of the boric acid volume used to decrease the power level and AO stability.

The currently operated mode (Mode 1) is characterized by high AO stability. When makeup is inserted into the coolant, it reduces power and increases AO. Insertion of the group reduces power too, but decreases AO. This combined impact on AO

Table 1 – Calculation results of parameters

Parameter	Mode 1	Mode 2	Mode 3
Boric acid volume used to decrease the power level, m^3	474.89	0	0
Instantaneous axial offset variation for the 3d and 101st cycle*, %	1.53 / 1.12; 3.46 / 1.81	10.90 / 9.26; 15.99 / 9.48	12.37 / 9.75; 15.02 / 9.98
Kq maximum value (Kq_{ac})	1.297 (1.35)	1.298 (1.35)	1.302 (1.35)
Coefficient of fuel energy potential utilization decrease	1.0025	1.0015	1.0013
Coefficient of natural uranium rate increase	0.9977	0.9961	0.9959
* – for power drop/for power increase.			

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provides for the opportunity to control the power density field. IAO deviation during the cycle is insignificant. According to the diagram in Figure 4, IAO values area in the acceptable area.

Nevertheless, the mode requires boron control for operation. It increases the amount of radioactive waste, personal radiation exposure and expenses for purchase of boric solution, distillate water, filters etc. Upon this, boron control is not automatized and requires additional time for core interaction starting (transport time). One of the fundamental principles of the Ukrainian nuclear operator's activity is the ALARA principle. In that case, the mode is acceptable for an insignificant number of LFM cycles (pilot operation), but undesirable for LFM industrial operation.

Modes 2 and 3 do not require boron control for power change during LFM. Nevertheless, they are characterized by high AO deviations. According to the diagram in Figure 5, IAO values are under the boundaries. It is acceptable only for power reducing, if the IAO returns to the boundaries in twelve hours [18]. Hence, the diagram demonstrates the compliance with the AO requirement.

The insertion of the group (groups) moves the power density field in the lower part of the core. Hence,

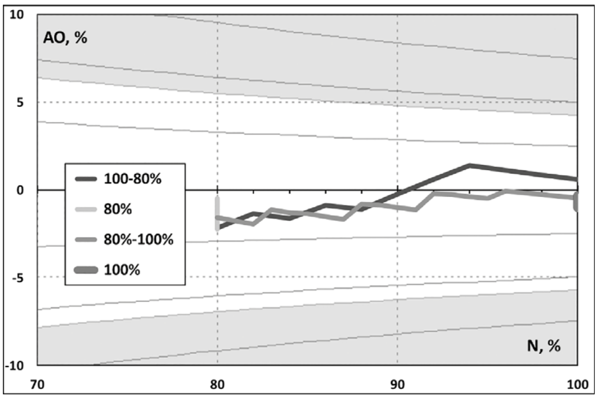


Figure 4 – Offset-power diagram for mode 1 during 24 hours of the 3d cycle

the reactor operator shall suppress xenon oscillations every cycle. It increases the probability of local power peaking and/or uncontrolled xenon oscillations. The mode is undesirable for LFM industrial operation. BC was implemented for compensation of slow reactivity variations due to xenon poisoning, compensation of group withdrawal and fuel burnup.

Conclusions

The research of the optimum mode for reactor power change in LFM for a common type of Ukrainian reactors is urgent and relevant.

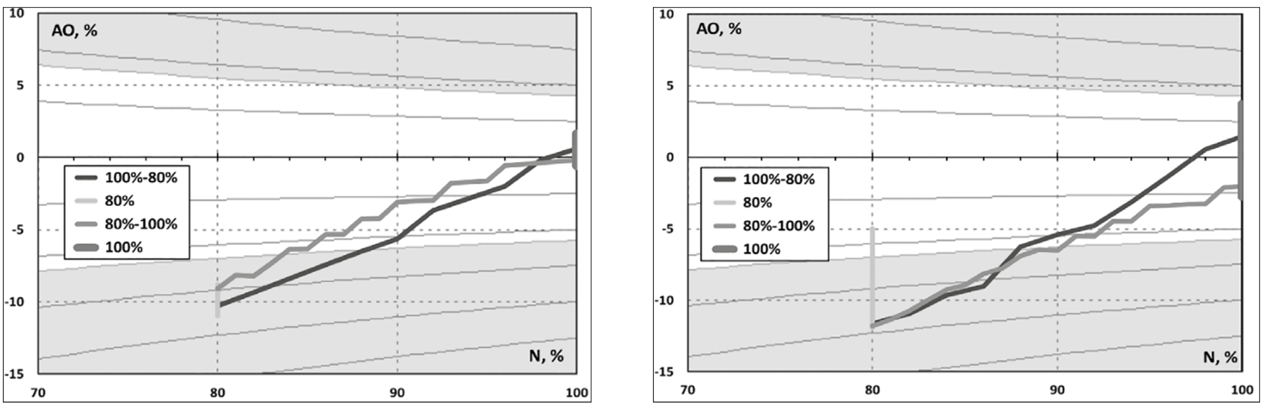
The paper contains the calculation of different load-following modes in the context of the boric acid volume used to decrease power level, axial offset stability, Kq maximum values and fuel utilization performance.

There are no significant differences between the modes in the context of fuel utilization performance, and they are characterized by acceptable Kq values.

Mode 1 currently operated for LFM is characterized by high axial offset stability, but it requires boron control for operation. Hence, mode 1 is not desirable for LFM industrial operation in the context of radioactive waste management. Upon this, boron control is not automatized for power changes and power density field control, requires additional time for core interaction starting (transport time).

Modes 2 and 3 do not require boron control for LFM power changes. Nevertheless, they are characterized by high axial offset deviations. Hence, the reactor operator shall suppress xenon oscillations every cycle. It increases the probability for local power peaking and/or uncontrolled xenon oscillations. The mode is not desirable for LFM industrial operation.

Following the above, the currently operated modes are acceptable for pilot operation of LFM, but not desirable for industrial operation, especially at several units. It is reasonable to develop some specific approaches for industrial operation that do not



a) b)

Figure 5 – Offset-power diagram for modes 2 (a) and 3 (b) during 24 hours of the 3d cycle

require boron control for LFM power changes and are characterized by high axial and radial offset stability. Following the above, it is reasonable to develop and implement a special mode for CR group operation during LFM.

References

1. Gilbert M. Masters, (2004). Renewable and efficient electric power systems. Stanford University, John Wiley & Sons, Inc., ISBN: 9780471280606. Retrieved from http://www.a-ghadimi.com/files/Courses/Renewable%20Energy/REN_Book.pdf.

2. Khalatov, A., Yushenko, K. (2012). Modern state and prospects of gas turbine technologies application in power and nuclear engineering, metallurgy and municipal energy systems of Ukraine. Part 1. *Industrial Heat Engineering*, 6, ISBN 0204-3602, pp. 30-45. Retrieved from http://dspace.nbuv.gov.ua/handle/123456789/60265.

3. EC JRC (2010). Load-following operating mode at nuclear power plants (NPPs) and incidence on operation and maintenance (O&M) costs. Compatibility with wind power variability. European Commission, Joint Research Centre, Institute for Energy, SPNR/POS/10 03 004 Rev. 05. Retrieved from http://www.publications.jrc.ec.europa.eu/repository/bitstream/111111111/15308/1/reqno_jrc60700_ldna24583enc.pdf%5B1%5D.pdf

4. IAEA (2010). Operating experience with nuclear power stations in member states in 2009. IAEA, Vienna, Austria. Retrieved from https://www.iaea.org/publications/8540/operating-experience-with-nuclear-power-stations-in-member-states-in-2009.

5. Ludwig, H., et al. (2010). Load cycling capabilities of German nuclear power plants. 55(8), *International Journal for Nuclear Power*. Retrieved from http://en.kernenergie.de/kernenergie/documentpool/AugSept/atw2010_09_waas_lastwechselfaehigkeiten_kkw_en.pdf

6. Jonas, P., et al. (2012). Additional costs for load-following nuclear power plants experiences from Swedish, Finnish, German and French nuclear power plants. Elforsk Rapport 12:71. Retrieved from https://energiforskmedia.blob.core.windows.net/media/21094/additional-costs-for-load-following-nuclear-power-plants-elforskrapport-12-71.pdf.

7. EUR (2001). The European Utility Requirement (EUR) document. Volume 2 Revision C.

8. EPRI (2008). The requirement for the load following and maneuvering capabilities of the nuclear power plants described in the Electric Power Research Institute (EPRI). Utility Requirements Document, Revision 10, EPRI, United States.

9. Lokhov, A., (2011). Technical and economic aspects of load-following with nuclear power plants. OECD/NEA. Retrieved from www.oecd-nea.org/ndd/reports/2011/load-followingnpp.pdf

10. YaB.0392OT-15 (2015). Report of the pilot operation results of the load-following mode at Khmelnitsky NPP Unit 2. SE «NNEGC «Energoatom», 218.

11. Andrushechko, S.A., et al. (2010). NPPs with WWER-1000. Moscow, Russian Federation. ISBN: 978-5-98704-496-4

12. Mokhov, V.A, Podshibiakin, M.A, (2010). Study of NPPs with WWER-1000/1200 reactors operation in the load-following mode. Proceedings of the Energia-2010 Conference, Moscow, Russian Federation. 103-106. Retrieved from www.energy2010.mpei.ru/_Files/Proceedings1.pdf

13. Maksimov, M., Pelykh, S., Cysel'ska, T., Baskakov, V. (2011). A way of the VVER-1000 neutron field axial distribution stabilization at power maneuvering. *Nuclear and Radiation Safety*. 1(49), ISSN: 2073-6231, 27-32. Retrieved from http://dspace.nbuv.gov.ua/handle/123456789/97037.

14. Baskakov, V., Maslov, M., Maslov, O. (2007). WWER operation algorithm to maintain the daily power system capacity balance. Odesa Polytechnic University, Proceedings, 2(28), 56-60. ISSN: 2076-2429. Retrieved from http://pratsi.opu.ua/app/webroot/articles/1312726750.pdf.

15. Dolgopolov, N. (2016). Development of the concept of the load-following mode for the WWER-TOI Reactor. Proceedings of MNTK-2016 Conference, Moscow, Russian Federation.

16. Nikolskiy, M. (2015). Axial offset as a measure of light water nuclear reactor sustainability. Odesa Polytechnic University, Proceedings, 1(45). ISSN: 2076-2429, 58-64. Retrieved from http://pratsi.opu.ua/app/webroot/articles/1428476242.pdf.

17. IAEA-TECDOC-911 (1996). Processing of nuclear power plant waste streams containing boric acid. IAEA, Vienna. ISSN 1011-4289. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/te_1325_web.pdf

18. 320.00.00.00.000.D61 Part 42.11 Reactor V-320. Technical characterization and information about safety. A-algorithms. OKB Gidropress, 3451-3500.

19. Filimonov, P., Mamichev, V., Averyanova, S. (1998). Reactor simulator program for modelling WWER-1000 load-following modes. *Atomic Energy*, 6, pp. 560-563.

20. 320.00.00.00.000.D61 Part 60. V-320 Reactor. Technical characterization and information about safety. Safety analysis report of the load-following mode pilot operation at Khmelnitsky NPP Unit 2. OKB Gidropress, 4651-4782.

21. SOU NAEK 064:2016 (2016). Requirements for documentation and calculation of neutron and physical characteristics of the core. NNEGCSE «NAEC «Energoatom», 48.

22. RK-D.0.41.566-12 (2012). Neutronic characteristics of WWER-1000 core. 21.

23. MT-T.0.18.411-15 (2015). Calculation methodology of the WWER-1000 fuel utilization.

Дослідження режимів зміни потужності ВВЕР-1000 для експлуатації у режимі добового регулювання потужності

Глушенков Р. С.

Державне підприємство «Національна атомна енергогенеруюча компанія «Енергоатом»

Українські атомні електростанції (АЕС) у базовому режимі виробляють приблизно 55 % від усього обсягу виробництва електроенергії в країні.

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Українська енергосистема стикається з дефіцитом електроенергії для режиму добового регулювання потужності (ДРП). Отже, доцільно розглядати можливість використання роботи АЕС в режимі ДРП. На цей час на енергоблоці № 2 Хмельницької АЕС завершено другий етап дослідної експлуатації режиму ДРП.

Виходячи з вищенаведеного, дослідження ключових аспектів впровадження ДРП на українських АЕС є нагальним та актуальним. Одним з ключових аспектів є визначення найбільш оптимального режиму зміни потужності реактора під час ДРП для найбільш розповсюдженого типу українських реакторів (ВВЕР-1000 тип В-320).

На ВВЕР-1000 поле енерговиділення та теплова потужність регулюються стрижнями та борним регулюванням. У статті описано дослідження стандартних режимів зміни потужності та контролю поля енерговиділення відповідно до вимог безпеки в контексті об'єму борної кислоти, який використовується для зниження рівня потужності, стабільності аксіального офсету, максимального значення коефіцієнта нерівномірності розподілу енерговиділення по ТВЗ (Kq) та ефективності паливовикористання (параметри).

Розрахункові результати параметрів отримані у ДП «НАЕК «Енергоатом» під час проведення нейтронно-фізичних розрахунків активних зон ВВЕР-1000 з використанням програми «БІПР-7А», в якій використовується математична модель реакторів ВВЕР. Розрахунок проводився для трьох режимів:

Режим 1 – органи регулювання систем управління і захисту (ОР СУЗ) групи 10 та борне регулювання: саме цей режим було обрано для дослідної експлуатації. Використання однієї регулюючої групи та борної кислоти/дистиляту дозволяють контролювати потужність та нерівномірність поля енерговиділення.

Режим 2 – Тільки ОР СУЗ групи 10: тільки одна регулююча група використовується для зміни потужності та контролю нерівномірності поля енерговиділення.

Режим 3 – Тільки ОР СУЗ груп 10, 9 і 8: всі регулюючі групи використовуються для зміни потужності та контролю нерівномірності поля енерговиділення.

Компенсація повільних коливань реактивності внаслідок отруєння ксеноном та вигоряння палива до/після зміни потужності проводилася борною кислотою для всіх режимів.

Результати дослідження визначають переваги та недоліки розглянутих режимів у контексті параметрів, а також шляхи вдосконалення системи регулювання потужністю та полем енерговиділення активної зоні ВВЕР-1000.

Ключові слова: аксіальний офсет, борне регулювання, ВВЕР-1000, ефективність паливовикористання, режим добового регулювання потужності, Kq.

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