Variable research of the efficiency of a combined thermal storage system when used at NPPs with VVER

Marat Murtazov[1], and *Valery* Yurin[2*]

[1]Yuri Gagarin State Technical University of Saratov, 77, Politechnicheskaya street, Saratov, 410054, Russia
[2]Federal Research Center "Saratov Scientific Center of the Russian Academy of Sciences", 24, Rabochaya str., Saratov, 410028, Russia

Abstract. The energy sector has the problem of covering the unevenness of daily energy consumption. Electric stations are unloaded during hours of reduced electrical load in the power system, which leads to a decrease in their economic efficiency and resource indicators. This problem is especially relevant for nuclear power plants. This is justified by their high cost with relatively cheap fuel, which makes it logical to fully load them. However, an increase in the number of nuclear installations in the energy system leads to the need to unload them. The authors developed a system for combining thermal accumulators (phase change accumulator and hot water tanks) with a nuclear power plant and an additional low-power steam turbine. An additional turbine makes it possible not to overload the main turbine of a nuclear power plant. In addition, when a nuclear power plant is de-energized, an additional turbine can provide power to the station's own needs using only the decay heat energy of one reactor. The conditions for economic efficiency and payback of the accumulation system were studied in the work. Boundary values of the maximum net present value for three steam turbine power options for a range of operating conditions were obtained.

1 Introduction

Electric stations are unloaded during hours of reduced electrical load in the power system, which leads to a decrease in their economic efficiency and resource indicators. This problem is especially relevant for nuclear power plants. This is justified by their high cost with relatively cheap fuel, which makes their base load logical. Thus, the energy strategy of the Russian Federation until 2035 obliges new generation nuclear power plants to participate in regulating uneven daily load patterns.

The authors of the article proposed a method of combining a nuclear power unit with a thermal storage system and an additional low-power steam turbine (Figure 1). The combination is aimed at increasing the utilization factor of the installed reactor power. A low-power steam turbine is necessary to maintain the operating mode of the main turbine of

* Corresponding author: urin1990777@bk.ru

a nuclear power plant unit and to reserve the station's own needs in the event of a complete blackout (more details below).

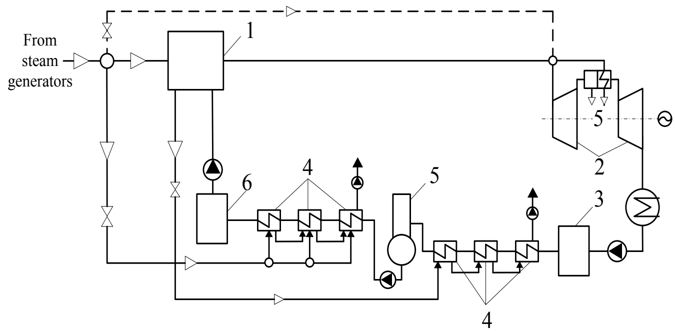

Fig. 1. NPP with an accumulation system: 1 –accumulator; 2 – turbine; 3, 6 – cold / hot tank; 4 – heat exchangers 5 – deaerator.

Batteries 1, 6 are charged with steam from the steam generators of the nuclear power unit. During hours of increased electrical load, hot water enters accumulator 1. Steam is generated there. The steam is sent to turbine 2. Eutectic compositions can be used as a heat-storing substance to obtain the required operating parameters: NaOH + $NaNO_3$, LiOH + LiCl and others. The material chosen for the study is NaOH + $NaNO_3$ [1].

2 Materials and methods

Elements of the theory of Markov processes were used to determine the main indicators of the reliability of power supply for the auxiliary needs of a nuclear power plant based on an additional turbine during a complete blackout. State graphs were constructed and described using differential equations, as a result of which the main reliability indicators of the proposed systems were found [2].

A comprehensive economic analysis of the proposed installations is based on a methodology for assessing the thermodynamic efficiency of cycles of thermal power plants and a methodology for assessing the technical and economic indicators of power generating installations. Also, the economic effect of risk reduction was taken into account based on the data obtained using the methodology for assessing the reliability of power supply for the NPP's own needs and statistical data on damage from accidents with melting of the reactor core.

The technical and economic calculation was carried out using the input data presented below. However, due to the complexity of international relations, prices are currently given in rubles.

As was shown earlier in [2], the installation of a low-power turbine at a nuclear power plant as part of a thermal storage system allows one to abandon the expensive heat exchangers of the reactor passive heat removal system (PHRS) while maintaining the required level of plant safety. According to open data on the supply of equipment to the Kursk NPP and Akkuyu NPP, the average cost of PHRS heat exchangers for one nuclear power unit is 1385 million rubles [3-5]. The high costs of maintaining a ready-to-operate state of the PHRS in the north reach 52 million rubles per year [6]. For calculations, the costs of PHRS as a positive substitution effect are taken to be 35 million rubles per year.

The average payment for capacity was taken based on [7]: 1283 thousand rubles per month. The options for the electricity tariff (sale from the station) during peak (accepted at the rate of 2 rubles/kW·h) and off-peak hours are taken on the basis of data from sources in

European countries, the USA [8-10] Main technical and cost characteristics off researched system are shown in Table 1.

Table 1. Main technical and cost characteristics of the thermal storage system.

Indicator name	Turbine power, MW				
Battery discharge, hours		4	8	12	16
1. Required amount of heat storage material for a phase change accumulator, tons	12	1100.6	2157.1	3213.7	4358.3
	62	5644.0	11062.2	16480.5	22350.2
	117	8113.3	15902.0	23690.7	32128.5
2. Preliminary volume of the phase change battery design, m^3	12	594.9	1166.0	1737.1	2355.8
	62	3050.8	5979.6	8908.4	12081.2
	117	4385.5	8595.7	12805.8	17366.7
3. Total cost of heat storage material for delivery and installation, million rubles	12	85.8	168.3	250.7	339.9
	62	440.2	862.9	1285.5	1743.3
	117	632.8	1240.4	1847.9	2506.0
4. Full cost of a phase change battery with a 20% surcharge for additional equipment, million rubles	12	32.3	62.5	92.7	125.4
	62	154.6	300.8	447.1	605.5
	117	233.7	455.2	676.8	916.8
4.1 Cost of a tube bundle with a lower manifold, million rubles	12	22.3	43.7	65.1	88.2
	62	108.1	211.9	315.7	428.1
	117	164.4	322.1	479.9	650.9
4.2 Cost of a tank with thermal insulation (phase change battery housing), million rubles	12	3.9	7.7	11.5	15.6
	62	18.8	36.9	54.9	74.5
	117	28.0	54.8	81.6	110.7
4.3 Cost of the separator drum, million rubles	12	0.7	0.7	0.7	0.7
	62	1.9	1.9	1.9	1.9
	117	2.4	2.4	2.4	2.4
5. Additional equipment, such as cold and hot water tanks, nitrogen station, million rubles	12	10.7	21.4	32.1	42.8
	62	55.3	110.7	166.0	221.4
	117	104.4	208.9	313.3	417.7
6. Total cost of the storage system main elements with 20% for delivery and installation, million rubles	12	128.9	252.2	375.5	508.2
	62	650.2	1274.4	1898.6	2570.2
	117	970.9	1904.5	2838.0	3840.6
7. Total cost of steam turbine shop equipment, million rubles	12	1076.0	1076.0	1076.0	1076.0
	62	2937.9	2937.9	2937.9	2937.9
	117	4528.8	4528.8	4528.8	4528.8
7.1 Steam turbine 12 MW, million rubles	12	572.0	572.0	572.0	572.0
	62	572.0	572.0	572.0	572.0
	117	572.0	572.0	572.0	572.0
7.2 Steam turbine 50/105 MW, million rubles	12	0.0	0.0	0.0	0.0
	62	1861.9	1861.9	1861.9	1861.9
	117	3452.8	3452.8	3452.8	3452.8
7.3 Additional capital investments for the modernization of electrical equipment, million rubles	12	504.0	504.0	504.0	504.0
	62	504.0	504.0	504.0	504.0
	117	504.0	504.0	504.0	504.0
8. Construction of the premises (accepted 20% of the total cost of the storage system design, million rubles	12	241.0	265.7	290.3	316.9
	62	717.6	842.5	967.3	1101.6
	117	1100.0	1286.7	1473.4	1673.9
9. Total capital investment in the thermal storage system, million rubles	12	1445.9	1593.9	1741.9	1901.1
	62	4305.7	5054.7	5803.7	6609.7
	117	6599.7	7719.9	8840.2	10043.3

Also, the effect of under-production of electricity into the power system when charging the battery was taken into account in the form of lost profit, which depends on the off-peak electricity tariff.

3 Results

The accumulated net discounted value (ANDV) and rate of return from the combination of a nuclear power plant unit with a thermal storage system is calculated according to the accepted conditions for off-peak tariff and turbine power options. The results are presented in Figures 2 and 3.

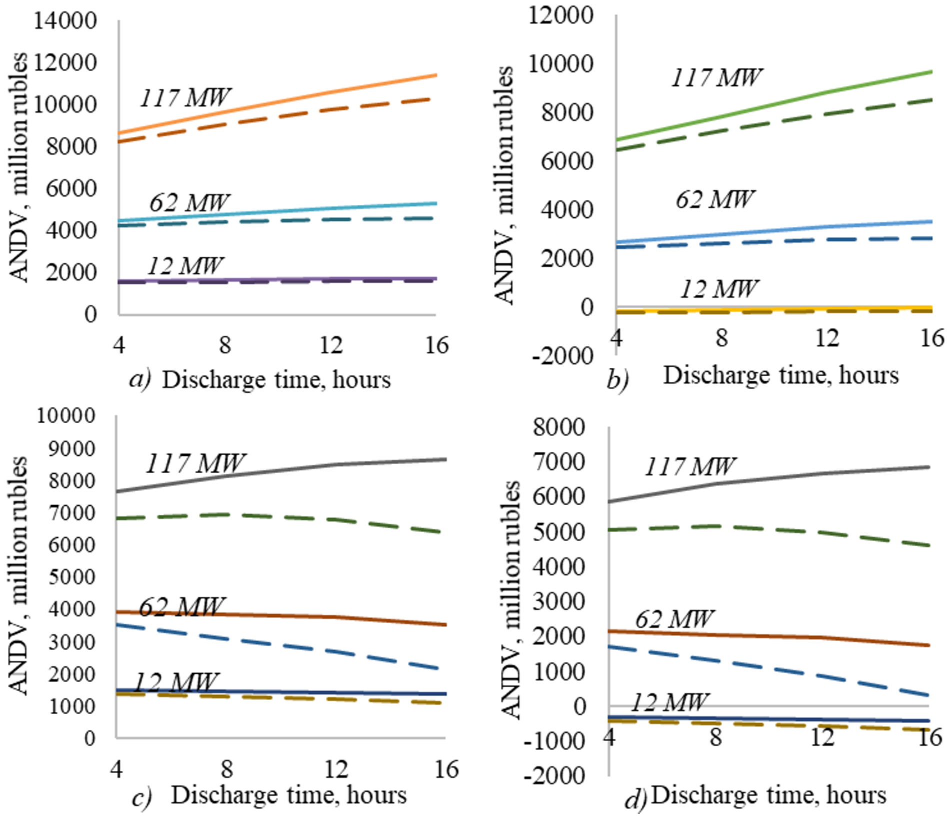

Fig. 2. Dependence of ANDV on discharge time for three steam turbine power options at different off-peak tariff costs a, c / b, d – taking into account / without taking into account the replacement of PHRS heat exchangers; a, b: ------ / - - - - - off-peak tariff is 0,1 rub/(kW·h) / 0.3 rub/(kW·h); c, d: ------ / - - - - - off-peak tariff is 0,6 rub/(kW·h) / 1,0 rub/(kW·h).

As can be seen from Figure 2, the maximum possible economic effect of the installation is achieved by increasing the turbine power. An increase in the off-peak electricity tariff leads to a negative dynamics of the economic effect with an increase in the number of hours of battery use due to the increase in the negative effect of underproduction of electricity into the power system during battery charging hours. The maximum effect (11.43 billion rubles) is achieved when using a turbine of maximum power, taking into account the replacement of PHRS heat exchangers, the maximum option for the number of hours of use and the lowest off-peak tariff.

As can be seen from Figure 3, taking into account the replacement of PHRS heat exchangers leads to the shortest payback period for the 12 MW steam turbine due to the largest share of the replaced investments compared to the higher power steam turbine options. The turbine with the highest power of 117 MW becomes the second most efficient when replacing PHRS (first in efficiency without taking into account the replacement of

PHRS) in terms of payback speed. This is justified by a reduction in specific capital investments in the installation with a significant increase in sold electricity. Moreover, in almost all cases, an increase in the number of hours of use leads to an increase in the payback period due to a corresponding increase in capital investments in the storage system at a constant specific cost of a turbine of the selected power.

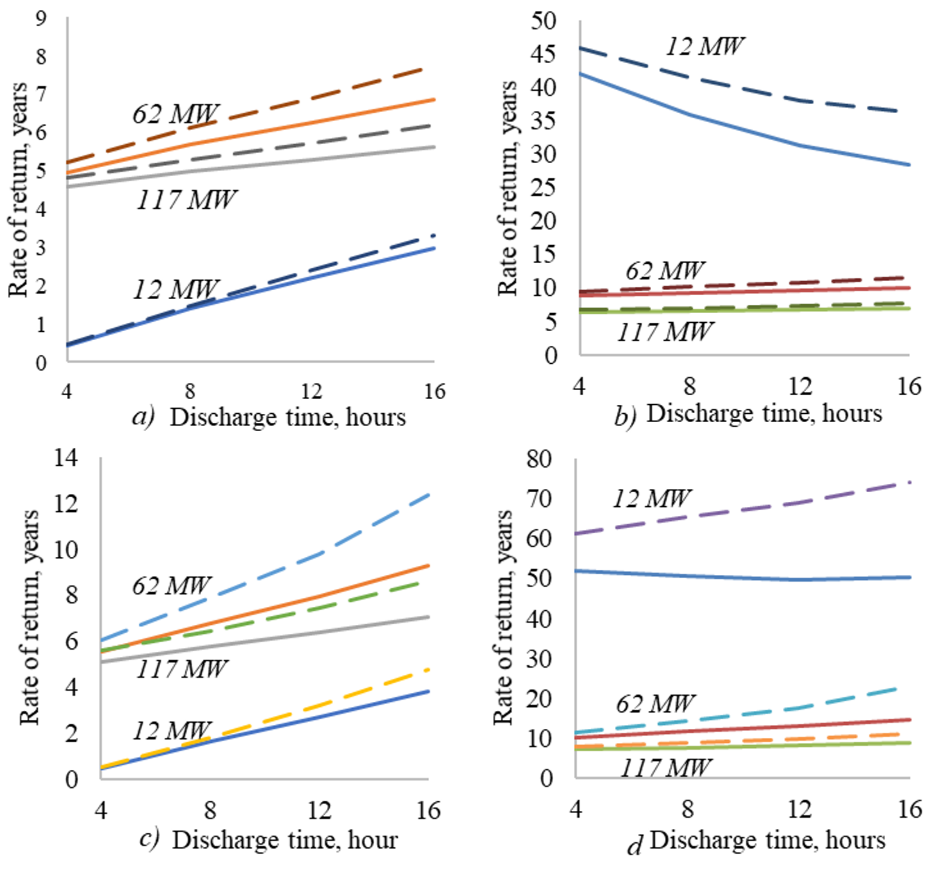

Fig. 3. Dependence of payback period on discharge time for three steam turbine power options at different off-peak tariff costs a, c / b, d – taking into account / without taking into account the replacement of PHRS heat exchangers; a, b: ------ / - - - - - off-peak tariff is 0,1 rub/(kW·h) / 0,3 rub/(kW·h); c, d: ------ / - - - - - off-peak tariff is 0,6 rub/(kW·h) / 1,0 rub/(kW·h).

4 Discussion

The study showed the high efficiency of combining a nuclear power plant with a thermal storage system for selected system conditions. However, each individual construction region requires a separate comprehensive study, taking into account all relevant system factors. In addition, it is necessary to experimentally clarify the operating characteristics of a phase transition battery, which can have a significant impact on the technical and economic indicators of the energy complex under study.

5 Conclusion

An energy complex based on combining a nuclear power plant with a phase change accumulator, a hot water tank and a low-power steam turbine has been developed. Storage systems allow a nuclear power plant to operate at the maximum utilization rate of the installed reactor power. The work analyzes the technical and system conditions under which the maximum economic effect is achieved. The boundary conditions under which the minimum payback period for investments is achieved are shown. The power options for the additional turbine (sum of turbines) were considered: 12 MW, 62 MW, 117 MW for 4, 8, 12, 16 hours of use per day.

References

1. M.A. Murtazov, Increasing the system efficiency of NPP based on high-potential thermal accumulation: dissertation. ...cand. technical sciences: 05.14.01. SSTU, Saratov (2022)
2. V.E. Yurin, Development of scientific foundations for ensuring the safety of nuclear power plants based on combination with multifunctional power generating installations: dis. ... doc. technical sciences: 05.14.01. SSTU, Saratov (2020)
3. Open competition in electronic form, The right to enter into an agreement for the supply of PHRS for the construction of power units No. 1 and No. 2 of Kursk NPP-2, https://zakupki.gov.ru/
4. Open competition in electronic form. The right to enter into an agreement for the supply of a passive heat removal system (PHRS) for the construction of power units 1, 2, 3, 4 of Akkuyu NPP, http://zakupki.rosatom.ru/20022595192026
5. Open competition in electronic form. The right to enter into an agreement for the supply of PHRS for the construction of power units 7, 8 of the Tianwan NPP and power units No. 3, 4 of the Xudapu NPP, https://energybase.ru/tender/b2b-center-2583524
6. R.Z. Aminov, A.N. Egorov, Atomic energy, Comparison and analysis of residual heat removal systems of reactors in station blackout accidents, **121**, 402-408 (2017)
7. Order of the FAS Russia dated December 15, No. 1222/20 (2020)
8. Average Power Plant Operating Expenses for Major U.S. Investor-Owned Electric Utilities, 2008 through 2018, https://www.eia.gov/electricity/annual/html/epa_08_04.html
9. Summer energy market and reliability assessment, Federal Energy Regulatory Commission, https://www.ferc.gov/market-assessments/reports-analyses/mkt-views/2017/2017-summer-assessment.pdf
10. European electricity markets panorama: France, AleaSoft Energy forecasting, https://aleasoft.com/european-electricity-markets-panorama-france