Efficiency investigation of the combined heat storage system using at NPPs with VVER

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Abstract. Using of consumer-regulators at NPPs will make it possible to increase the share of nuclear power plants in the power system due to the expansion of their use range with a constant installed capacity utilization factor of reactors. As a result, the renewal of the maneuverable capacities of the power system can be carried out with the reduction of power plants, operating on fossil fuel, which will lead to a decrease in emissions causing irreparable harm to the environment. In the article, the heat storage system developed by the authors is presented and researched. It includes a phase change accumulator, cold and hot water tanks and additional steam turbines, which will avoid expensive main turbine modernization and its deterioration magnification, also it will provide an additional reserve for the NPP's own needs. The results of investigation conducted for a wide range of operating conditions have shown that systems pay off completely under certain conditions. The authors also showed that the installation of a hot water tank can reduce capital investment in a heat storage system based on a phase change accumulator.

1. Introduction
Nuclear plants are already involved in regulating of energy loads nonuniformity in power systems in many countries. This need is associated with the growing share of nuclear power plants in the power supply market. Fulfillment of this requirement reduces the installed capacity utilization factor of reactors, which, together with the high cost of building nuclear power plants, significantly reduces their competitiveness.

Combining nuclear power plants with storage systems can be one of the ways to improve the maneuverable characteristics of nuclear power plants while maintaining a high installed capacity utilization factor of reactors. The system developed by the authors includes a phase change accumulator and cold and hot water tanks. Additional steam turbines can also be installed in conjunction with a heat storage system, which will avoid expensive main turbine modernization and its deterioration magnification.

2. Materials and methods
The storage system developed by the authors can be used to implement the presented concept. The structure diagram is shown in figure 1.
The structure diagram of the NPP combination with a heat storage system: 1 – phase-transfer accumulator; 2 – additional steam turbine; 3 – electric generator; 4 – deaerator; 5 – condenser; 6 – pump; 7, 10 – cold / hot water tank; 8, 9 – first / second stage heat exchangers.

During the hours when the electrical load is reduced, part of the main steam is directed to charge the accumulators. The steam condensate is directed from the phase change accumulator 1 to the first stage heat exchangers 8, where the feed water is heated. Thereafter, steam condensate is directed in the main steam turbine circuit. Part of the selected main steam is directed to the second stage heat exchangers 9, where the feed water is heated. The steam condensate is mixed into the regenerative circuit of the main steam turbine. The excess of the main steam is generated by increasing the temperature of the feed water at the same reactor power. This partially compensates for the regenerative bleeding off the main steam for charging the storage system. Steam turbines 2 work in idle mode. In the mode of increasing the electrical load, feed water is directed from the hot water tank 10 to the phase change accumulator 1. The generated steam is directed to additional turbines. The condensate is directed to the cold water tank 7.

On the basis of works [1-3], the authors have developed the design of the phase change accumulator, which is capable of operating in the steam generation mode [4]. NaOH + NaNO₃ material satisfies the operating conditions and operating mode of the accumulator [5-7]. The analysis of the sources [8-12] makes it possible to conclude that the selected heat storage material has a sufficient number of operating cycles (up to 4000) without a significant decrease in thermophysical properties under the selected conditions. After that, the decrease in the melting temperature and in the heat of the phase change can be up to 4-7% over the service life. In the work, the negative factor of deterioration of the heat storage material properties is taken into account in the form of an annual decrease in electricity generation by 0.4%.

The pressure decreases in the hot water tank during discharging and the water evaporates. Pumping a nitrogen cushion into the tank will solve this problem. Such a solution will create an overpressure in the hot water tank, which will be a natural height of damming when hot water is directed to the phase-transfer accumulator during high load hours.

The investigation was carried out on the example of nuclear power plant with VVER-1000. According to the requirements of the Unified Energy System of Russia nuclear power plants with VVER should participate in the primary regulation of the power system current frequency, including they should provide a 2% increase in power at the request of the system operator. For this the installation of additional steam turbines with a total capacity of 87 MW is required. Then, in the normal mode, they will be able to operate at a reduced power of 65 MW (75% of the nominal) and, if necessary, supply an additional 22 MW to the power system, which is 2% of the total capacity of the power complex NPP + storage system. This level of reduced load is realized with multiple steam nozzle control without significant losses in the efficiency of steam turbines. The power of additional
steam turbines is selected so that one of them has a power of 12 MW, which, according to [13], will make it possible to ensure reliable reserve of own needs of two NPP power units. Thus, the capacity of the second turbine will be 75 MW.

During off-peak hours of electrical load, the main steam is directed from the steam generators to charge the heat storage system for 5 hours at a flow rate of 370 kg/s. During peak hours, hot water is supplied from the hot water tank to the phase change accumulator with a temperature of 258°C and a total flow rate of 81.6 kg/s within 15 hours. Additional steam turbines work in idle mode during the remaining 9 hours with a main steam flow rate of 8.7 kg/s (0.556% of total main steam flow rate). The total energy is required to operate the phase change accumulator for 15 hours – 2068 MWh, for this, the heat storage material is required in the amount of 24953 tons. As an alternative the heat storage system without a hot water tank was investigated in order to justify the need to install this tank. According to an alternative scheme, cold water enters the charged phase change accumulator during the peak load hours of the power system with a temperature of 25°C. The water is heated to a temperature of 258°C and vaporized. The total energy is required for the operation of the phase change accumulator for 15 hours - 3320 MWh, for this, heat storage material is required in the amount of 40035 tons. The generated steam is also directed to additional steam turbines. The accumulator is also charged by taking the main steam from the steam generators during the hours when the electrical load is reduced.

3. Investment and annual operating costs

One multifunctional steam turbine with a capacity of 12 MW is capable of providing reliable redundancy for auxiliary needs of two NPP power units [13]. This makes it possible to abandon the expensive heat exchangers of the passive residual heat removal (PRHR) system, which should be taken into account in the economic effect. The cost of PRHR heat exchangers is assumed to be $16.8 million per power unit. Additional equipment is estimated at $3.8 million. The total cost - $20.6 million. Annual operating costs range from $0.05 to $0.27 million depending on climatic conditions [14]. Annual operating costs of $0.14 million and annual inflation of 3% are taken for calculations.

Investments in the equipment of the phase change accumulator are taken in the article on the basis of the analysis of existing heat exchangers, which are similar in design to the accumulator, taking into account a 100% extra charge for delivery and assembly. The cost of heat storage material is taken equal to 1.8 $/kg [5-7; 15-16]. The price includes: cost of material 0.52 $/kg, delivery, customs payments and other deductions. Specific capital investments in the steam turbine unit, related equipment and modernization amounted to about $646/kW for 12 MW, $417/kW for 75 MW, according to analytical information for 2018 [13].

The accumulated experience in the design of hot water tanks allows us to take preliminary capital investments in their construction - $265/m³ [17]. Delivery and assembly of equipment are taken into account in the form of a surcharge of 30% of the cost of the tanks. The use of a compressor station is necessary for the use of a nitrogen blanket in the tanks. According to [18, 19], the preliminary cost of such equipment will be about $1.35 million, taking into account the cost of delivery and assembly - $1.62 million. Electricity consumption will be about 0.2 MW/h. Thus, the annual cost of its operate will amount to about $0.0017 million. The cost of a building erection is assumed to be 20% of the cost of the heat storage system.

4. Results

To determine the final economic efficiency of the developed system, the electricity market of the European countries, the US and the RF was researched. Electricity rates vary depending on the time of day, region and a number of factors. The off-peak tariff becomes significantly cheaper due to a significant reduction in electricity consumption. The off-peak electricity tariff is accepted for calculations in the range of $0 - 0.02/kWh. Three options of the selling tariff for electricity during the hours of increased load were taken on the basis of data from sources in European countries, the
USA and the Russian Federation [20-23]: 0.02 / 0.04 / 0.06 $ / kWh. Inflation was taken into account, when the accumulated net present value (ANPV) was calculated, in the amount of 3%.

The results of the economic analysis of combining an NPP power unit with a VVER-1000 with the developed heat storage systems are shown in figure 2.

**Table 1. Cost characteristics.**

| Equipment / Value, $ million | With hot water tank | Without hot water tank |
|-----------------------------|---------------------|------------------------|
| Heat exchange tube bundle with collector | 10.3 | 16.2 |
| Jar with thermal insulation | 0.7 | 1.1 |
| Drum separator | 0.2 | 0.2 |
| The main structural elements of the phase change accumulator with a 20% surcharge, for delivery and assembly | 13.4 | 21.0 |
| Storage material | 44.9 | 72.1 |
| Nitrogen-compressor station with a 20% surcharge, for delivery and assembly | 1.6 | - |
| Steam turbine 12 / 75 MW | 8.8 / 40.1 | 7.6 |
| Modernization of electrical facilities and automated process control system of the NPP | | |
| Building erection | 14.9 | 15.5 |
| Total investment | 134.3 | 165.1 |

The results of ANPV calculations at the selling tariff for electricity during the hours of increased load - 0.06 $ / kWh are not shown in figure two, since for these options the income for the billing period is negative at any value of the off-peak electricity tariff. As Figure 2 shows, using a hot water tank can increase the profitability of the system by reducing the investment in the heat storage system (table 1).

5. Discussion
Thus, the system pays for itself within the billing period (25 years) only with the largest of the options of the selling tariff for electricity with increased energy consumption (0.06 $ / kWh) adopted in the work: with an off-peak selling rate in the range of 0 - 0.007 $ / kWh for a heat storage system without a hot water tank and 0 - 0.018 $ / kWh for a system with a hot water tank.

In this way, the installation of a hot water tank makes it possible to reduce the investment in a heat storage system based on a phase change accumulator and to obtain higher economic efficiency indicators. In addition, using of a multifunctional additional steam turbine as part of the heat storage system makes it possible to abandon the installation of expensive heat exchangers of the passive
residual heat removal system and related equipment, which also contributes to an increase in the economic efficiency of the power complex.

6. Conclusion
In the article, the efficiency of the heat storage system developed by the authors, which includes a phase change accumulator, cold and hot water tanks, as well as additional steam turbines, was investigated. The results of the investigation showed that using of a hot water tank allows to reduce investment in a heat storage system based on a phase change accumulator. The methodology used and the results obtained can be used for scientific substantiation and further development of technologies for environmentally clean electricity production based on the combination of heat storage systems and nuclear power plants.

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