Primary control of current frequency in energy system based on a two-circuit NPP using a heat accumulation system

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Abstract. A principle schema of an energy complex, including a two-circuit nuclear power plant, a heat phase transition accumulator and an additional steam turbine was developed and investigated. In the course of the work, well-known systems containing phase transition accumulators were analyzed. The known devices are designed only for heating hot water and can not be used to generate steam. To ensure the operation of the heat accumulation system under the required conditions, the design of a heat accumulator with a phase-transition material has been developed. The technical result of the development is to ensure the constructive capability of phase transition accumulators to operate in the steam generation mode. Investigations have shown that the development of heat accumulation systems at nuclear power plants will make it possible for NPP to perform the requirements of System operator of Unified Energy System of Russia about involved in primary control of current frequency, without reduce in the coefficient of the reactor power utilization. This will help to increase the efficiency of energy generating capacities structure, with the possibility of increasing the share of powerful nuclear power units in power systems, and to increase the competitiveness of nuclear power plants in the electricity market.

According to the Technical requirements for generating equipment of participants in the wholesale market, approved in 2017 by Deputy Chairman of the Management Board of RAO «Sistemnyj operator Édinoj ehnergeticheskoj sistemy Rossiio» (Unified Energy System of Russia) S.A. Pavlushko: “All of the included generating equipment should be involved in primary control of current frequency, with the exception of power units of nuclear power plants with fast neutron reactors, and also with high power canal reactors and until 2016 with water-water power reactors that was put into commercial operation until 2009”.

To participate in primary control of current frequency, the maneuverable characteristics of the generating equipment of NPPs with VVER-type reactors at frequency deviations should ensure guaranteed participation of generating equipment in primary control of current frequency by realizing the required primary power within the control range: for loading up to 2% or for unloading up to 8% of the rated electric capacity of the power unit. For this, the current capacity of the reactor should be maintained at a level not exceeding 98% of the rated thermal power. The fulfillment of this requirement significantly reduces the coefficient of the reactor power utilization, and hence the performance indicators of nuclear power plants.

In addition, in the Unified Energy System of Russia the deficit of peak and semi-peak capacity, capable economically and reliably providing nuclear power plants with a basic load, traces. At the same time, in the structure of the generating capacities of the Russian Federation European part an
active growth in of the nuclear power plants share traces, which further exacerbates the problems of providing them with basic loading. One of the ways to solve these problems, the combination of nuclear power plants with facilities that allow to accumulate energy can be.

Most known accumulating systems involve the use of accumulated heat in the main cycle of nuclear power plants, which will entail a costly modernization of the basic steam-turbine unit (STU) and electric generator. In addition, the wear of the main equipment will increase with load increasing. In the present work proposed the install of additional STU together with heat accumulation systems, which will allow to avoid expensive modernization of the basic STU and increasing its wear.

With the use of heat accumulation systems, including an additional STU, the reactor installations will be able to continue working with the same high coefficient of the reactor power utilization. At the same time, during the hours of reduced power load, a part of the main steam will be sent to the accumulator, due to which the power generated by the basic STU will decrease. At the request of the system operator of the power system, if necessary to increase the power, the steam, directed to the accumulator, directs to the basic STU, and thus, generated by NPP power is increased. In the process of discharge, the stored heat can be used to generate steam, which acts as a working fluid in an additional steam turbine. The capacity of the additional STU is selected in such a way that the reserve of its capacity (from 75% to 100%) is equal to 2% of the total capacity of the considered power complex NPP + heat accumulation system + additional STU. With nozzle governing of steam, additional STU can be maintained at 75% power with high coefficient of efficiency. Then, at the request of the system operator, it is possible at any moment to increase the capacity of the additional STU to 100% and ensure rise in the capacity of the power complex NPP + heat accumulation system + additional STU on 2%.

A principle schema of an energy complex, including a two-circuit nuclear power plant, a heat phase transition accumulator and an additional steam turbine is shown in Fig. 1.

![Figure 1](image-url)

**Figure 1.** The system for increasing maneuverability of a two-circuit nuclear power plant: 1 – reactor; 2 – steam generator; 3 – steam distribution device; 4 – basic steam turbine; 5 – additional steam turbine; 6 – electric generator; 7 – the condenser; 8 – condensate pump; 9 – low pressure heaters; 10 – deaerator; 11 – feed pump; 12 – high-pressure heaters; 13 – heat phase transition accumulator; 14 – main circulation pump; S – separator; IS – intermediate superheater.

In the operational mode, during the night off-peak hours of the load in the power system, the heat accumulator 13 is charged by supplying main steam from the steam generator 2. The steam condensate
after the heat accumulator 13 is directed to the feed water train after high-pressure heaters 12. During the mixing process, the temperature of the feed water increases, as a result of which additional flow-rate of steam are generated (at the same reactor power). The additional steam partially compensates the steam consumption for charging the accumulator. The additional turbine 5 stops or operates in idle mode by taking a small flow-rate of main steam after the steam generator.

In peak and semi-peak loads, part of the feed water after the high-pressure heaters 12 directs in the heat accumulator 13, where, by using the accumulated heat, the steam is generated and directed to an additional STU 5. After an additional STU 5, steam condensate is directed to the regeneration system of the basic STU 4. It should be noted that due to the increase of feed water flow rate through the regeneration system, there will be some reduction of the basic STU 4 capacity, because the steam extraction for regenerative heaters will increase.

In the course of the work, well-known systems containing phase transition accumulators were analyzed. The known devices using the phase transition latent heat of the heat-accumulating material are designed only for heating hot water and can not be used to generate steam, because the corresponding technical solution is not provided. To ensure the operation of the heat accumulation system under the required conditions, the design of a heat accumulator with a phase-transition material has been developed (figure 2) [1]. The technical result of the development is to ensure the constructive capability of phase transition accumulators to operate in the steam generation mode.

![Figure 2](image_url)

**Figure 2.** Design of heat steam generating phase transition accumulator: 1 – level transmitters; 2 – higher drum-type steam separator; 3 – overhead traveling crane; 4 – steam conductor; 5 – breathing hole; 6 – tube sheet; 7 – jar; 8 – metal heat exchange tube bundle; 9 – lower drum; 10 – downtake tube; 11 – pipeline; 12 – glass tubes, in which the parameters control sensors of the heat-accumulating material are located.

Main steam in the process of charging is directed through the steam conductor 4 to the higher drum-type steam separator 2. When discharged, the steam, generated in the higher drum-type steam separator 2, directs through the steam conductor 4 to the additional steam turbine. Inside the accumulator jar, there is a vertical metal heat exchange tube bundle 8, through which the heat transfer agent flows (condensate from main steam during the charging process or generated steam-water mixture during the discharge of the accumulator). In the lower part of the jar 7 there is a lower drum 9, designed to distribute the main flow of heat transfer agent uniformly through the heat exchange metal tubes 8 during the discharge hours and to collect condensate during the charging of the accumulator.
To compensate the expansion of the heat-accumulating material, when its aggregate state is changed, free space is provided in the inner higher part of the jar 7, and in the tube sheet 6 the breathing hole 5 is installed to maintain a constant pressure in the inner space of the jar 7 when the aggregate state of the heat-accumulating material changes. The process of removing used heat-accumulating material is possible only in the melt state. For this purpose, a downtake tube 10 is provided at the bottom of the jar. In the hole of the downtake tube 10, pipeline 11 is provided. Through it the formed condensate is taken away during the charging hours, and during the peak hours the feed water is supplied.

As a heat accumulator working medium, various materials can be used, such as: stones, oils, gases, eutectic salts, including those with latent heat of phase transition [2, 3]. The alloy LiNO$_3$ was widely distributed as heat-storage material [4, 5, 6]. However, the melting temperature LiNO$_3$ (253°C) does not allow using it in the required temperature regime. To obtain the required melting temperature (272°C), it is possible to use an alloy, consisting of LiNO$_3$ and NaCl [3, 7, 8].

| Alloy name                | Melting temperature, °C | Latent heat of melting, kJ/kg | Density, kg/m$^3$ | Heat capacitance, kJ/(kg·K) |
|---------------------------|-------------------------|-------------------------------|-------------------|-----------------------------|
| LiNO$_3$                  | 253                     | 530                           | 1776              | 2.04                        |
| 91%LiNO$_3$+9%NaCL         | 272                     | 528.2                         | 1755.21           | 2.091                       |

For calculations it is assumed that an additional STU in the charging mode during the night off-peak hours of the load is shut down off or idling (8 h), and the rest of the time (16 h) at reduced load 75% in order to ensure the requirement of Unified Energy System of Russia for the participation of NPP in primary control of current frequency.

The calculations were carried out using the example of a power unit with a VVER-1000 reactor. To carry out a study of economic efficiency, the increase in the output capacity of nuclear power plants (taking into account the losses from the decrease in the power of the main STU) was taken at 87 MW (the capacity of the additional STU at the same time is 117 MW). To enable participation in primary control of current frequency, the additional STU will operate at 75% capacity (88 MW), that is, the increase in capacity, generated at nuclear power plants, taking into account the losses on the main STU, will be 65 MW. Due to the fact that the additional STU will supply 75% capacity to the energy system within 16 hours, it will be possible to gain 2% capacity of the energy complex NPP + heat accumulation system + additional STU (from 1065 MW to 1087 MW) at the request of the System Operator of the Unified Energy System of Russia.

Calculations showed, that generation of excess of main steam with a flow rate 168 kg/s is necessary to obtain the required power. To ensure the required flow rate in the peak and half-peak hours, it is necessary to accumulate about 10500 MW·h of heat energy during off-peak hours. For this, 53% of the total amount of main steam should be direct to the accumulator charging for 8 hours during night off-peak hours.

Because of little research into the field of heat energy accumulation on the basis of a phase transition, a problem arises in estimation of capital investments in a phase transition accumulator. However, based on the analysis of existing analogs and standard designs, it is possible to take some average cost of the main technical units of the installation under investigation (table 2).

Based on group TURBOPAR Company data, specific investments into the low-power steam turbine of the required capacity are about 27 thousand rubles / kW. Therein, we took into account costs of the condenser and electric generator of the additional steam turbine. Additionally, it was take into account modernization of the transformer cooling system, installation of a high-voltage transformer, modernization of the cooling system of the conductors, modernization of automated control systems of technological processes, and assemblage of steam turbines [9].
Table 2. The cost-constructive characteristics of a heat accumulator.

| Name of the parameter                                      | Value    |
|-------------------------------------------------------------|----------|
| Heat-accumulation material mass, t                          | 42726    |
| Volume of heat accumulator, m^3                             | 25841    |
| Pipe bundle (maximum allowable pressure level – 8 MPa), million rubles | 1620     |
| Heat accumulating material, million rubles                  | 1220     |
| Drum-separator and other auxiliary equipment, million rubles | 651      |
| Mounting and start-up, million rubles                       | 524      |
| Total investment in the installation, million rubles        | 4015     |

For calculation purposes, the tariffs for electricity and fuel prices were taken from the forecast relating the long-term socio-economic development of the Russian Federation provided by the Ministry of Economic Development of Russia. As calculations showed, the net discounted income for the accounting period of 25 years was 4750 million rubles. At the same time, investment was fully paid off in 16 years.

Conclusions
The development of heat accumulation systems at nuclear power plants will make it possible for NPP to perform the requirements of System operator of Unified Energy System of Russia about involved in primary control of current frequency, without reduce in the coefficient of the reactor power utilization. This will help to increase the efficiency of energy generating capacities structure, with the possibility of increasing the share of powerful nuclear power units in power systems, and to increase the competitiveness of nuclear power plants in the electricity market.

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