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Nuclear power plant safety improvement based on hydrogen technologies

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Abstract

An effective application for hydrogen technologies at nuclear power plants is proposed, which improves the plant maneuverability during normal operation, and provides for in-house power supply during the plant blackout. The reliability of the NPP's emergency power supply was assessed probabilistically for the plant blackout conditions with the simultaneous use of an auxiliary full-time operating steam turbine and the emergency power supply system channels with diesel generators. The proposed system with an additional steam turbine makes it possible to use the reactor core decay heat for the reactor shutdown for 72 h. During the blackout at a plant with several units, the additional steam turbine power required for the unit cool down is maintained by additional steam generated by the combustion of hydrogen in oxygen. It has been shown that the proposed flowchart with an auxiliary full-time operating small-power steam turbine installed at the NPP, combined with an integrated hydrogen facility, improves the reliability of the NPP in-house power supply during blackout accidents.

Keywords: Emergency power system; Hydrogen cycle; Combustion chamber; Nuclear power plant; Flexibility; Safety; NPP in-house power backup; Blackout.

Introduction

The world has seen a large number of major system accidents resulting in forced shutdown and blackout of generating facilities. For nuclear power plants, this problem is becoming extremely important in connection with the requirement to ensure the reactor core cool down. Based on data from Atomenergoproekt Institute, it has been shown on the example of Balakovo NPP's unit 4 that loss-of-power events contribute the greatest to the potential reactor core damage frequency (51.4%).

At present, in the event of the blackout, the NPP will change over to the reactor cool down mode with power supplied from diesel generators [1]. In this case, the main circulation pumps shut down, leading to a pressure increase in the secondary circuit, actuation of BRU-As (fast-acting steam dump valves with discharge to the atmosphere) and of the steam generator relief valves, and accordingly, to the steam release into the atmosphere.

To exclude the fluid loss through the secondary circuit relief valves and to avoid the negative effects it might entail, the preferred option is to cool down the reactor in the standard mode without the BRU-A actuation, i.e. to keep the circulation pump in operation and to discharge a portion of the steam not spent in the auxiliary turbine to the condenser through BRU-Ks (fast-acting steam dump valves with discharge to the turbine condenser).

Theoretical part

During loss of power, one of the ways to cool down the reactor in the standard mode is to cool it down with in-house power supplied from the auxiliary turbine plant, which operates on the steam generated thanks to decay heat and the energy from the combustion of hydrogen in oxygen [2].

To improve the efficiency of the full-time operating auxiliary turbine, this paper considers a flowchart with the accumulation of unspent electric energy in the form of hydrogen and oxygen in the nighttime off-peak load hours and the use of this energy for superheating the steam coming to the secondary turbine during peak hours. In this case, the auxiliary turbine and the hydrogen facilities might be deployed off-site. A possible flowchart for

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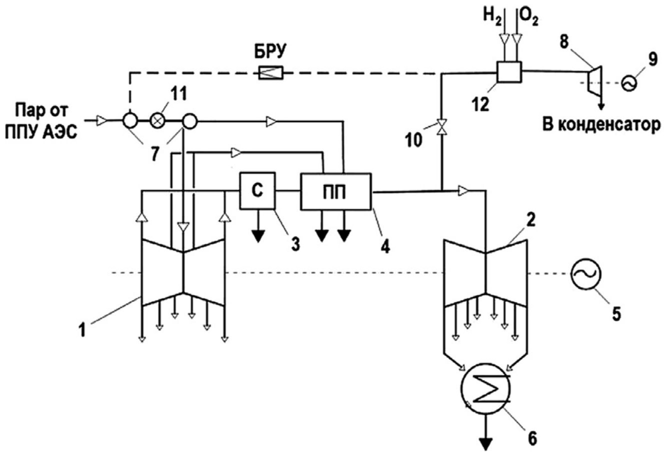

Пар от ППУ АЭС = Steam from NPP SSS (steam supply system)

БРУ = BRU

С = S (separator)

ПП = SS (intermediate steam-to-steam superheater)

В конденсатор = To condenser

Fig. 1. Flowchart for the plant backup with improving the NPP maneuverability using an auxiliary steam-turbine plant: 1, 2 – steam turbine's high- and low-pressure cylinders, respectively; 3 – separator; 4 – intermediate steam-to-steam superheater; 5 – electric generators; 6 – condensers; 7 – steam distribution device; 8 – auxiliary steam-turbine plant; 9 – auxiliary steam-turbine plant's generator; 10 – gate valve; 11 – cut-off valve; 12 – two-stage combustion chamber with water-steam cooling.

Мощность остаточного тепловыделения, МВт = Decay heat power, MW

Время расхолаживания, ч = Cooldown time, h

Fig. 2. Diagram for an approximate estimate of decay heat after shutdown of the nuclear facility.

implementing the above approach for a power unit of a wet-steam NPP is shown in Fig. 1.

An additional amount of steam needed for the operation of the auxiliary turbine plant can be obtained by increasing the reactor power, as the result of which the capacity of the high-pressure cylinder will increase, and the low-pressure cylinder will avoid overloading through a portion of the steam being fed to the auxiliary steam turbine after intermediate superheating.

The auxiliary steam-turbine plant is continuously in operation, i.e. in the daytime it is used for peak electric energy production and in the nighttime it has its load reduced to the minimum. In an emergency, caused, for example, by a loss of power, the auxiliary turbine continues to be fed with the steam generated by decay heat. As its amount goes down, the combustion chamber starts to be fed with accumulated hydrogen and oxygen and injected with ballast water, which results in the formation of the steam amount required for power maintenance.

After its shutdown, any reactor will have heat release taking place therein due to the absorption of the fission fragment radioactive transformation products (beta-particles and gamma-quanta). This is traditionally referred to as decay heat. The variation in the decay heat power depending on these processes for VVER-1000, as calculated using the Way-Wigner formula [3], is shown in Fig. 2.

At the initial stage of the cool down, natural convection is maintained in the primary circuit by means of the heat removal through the steam generator (at a rate of not more than 15 °C per hour). At the same time, the required portion of the steam generated by the reactor core decay heat is fed to the steam turbine from the steam generating device. The rest of the steam is discharged to the condenser through the BRU-Ks.

Four power units require at least two steam turbines (one for the first and one for the third or one for the second and one for the fourth unit depending on the refueling sequence). We shall consider the worst-case scenario when one of the auxiliary steam-turbine plants is out for repair, while all units are in operation, and the four units are cooled down by means of one auxiliary turbine using the decay heat from one reactor; all of the steam generated in the remaining three turbines is discharged to the condenser through the BRU-Ks. The pressure at the turbine inlet is maintained equal to the standard pressure by means of the BRUs.

Decay heat from one VVER-1000 reactor is enough for the auxiliary turbine plant to generate the electric energy required for cooling down one unit for 72 hours. In the event of two power units, the decay heat from one reactor will suffice for eight hours. For four power units, this time decreases to approximately one hour. During this period, the two-stage hydrogen combustion chamber with water-steam cooling is rendered operational. In the next two hours the hydrogen combustion chamber operates only for superheating the live steam produced in the main steam generator. Further on, live steam stops to be sufficient for the required power production, and for up to eight hours after the accidents starts, the hydrogen combustion chamber operates with the purpose of generating the deficient amount of steam (through the ballast water injection into the combustion chamber) and superheating the live steam from the main steam generator. After eight hours from the start of the accident, the hydrogen combustion chamber starts to operate as an independent steam generator, and the steam produced in the main steam generator is discharged to the condenser through the BRU-Ks. After about 10 hours from the start of the accident, the primary coolant