Operating characteristics and peak regulation capability of AP1000 nuclear power unit

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Abstract. In recent years, with the operation of large capacity nuclear power units, it has brought great challenges to the peak regulation on the grid side. From the design concept and practical operation point of view, this paper studies the operation characteristics of the AP1000 nuclear power unit, analyzes its peak shaving capacity, puts forward three peak shaving modes, analyzes the impact of nuclear heating on peak shaving, and gives suggestions for peak load regulation.

1. Overview of Nuclear power Development
Nuclear power is a clean, safe, mature technology, strong supply capacity, and large-scale application of power generation. The application of international nuclear energy has undergone a process of continuous improvement from the first generation to the fourth generation of nuclear power plants. China's nuclear power has entered the development stage from the beginning and has the ability to independently design and build nuclear power. China has made a major decision to actively promote the development of nuclear power. Speeding up the construction of nuclear power and increasing the proportion of nuclear power in the power supply will help to alleviate the contradiction between power growth, transportation and environmental protection, and the development prospect of nuclear energy utilization will be more and more broad.

At present, the Haiyang Nuclear Power #1 and #2 units of the State Power Investment Corporation in Shandong Province have been put into operation. During the construction of the Huaneng Shidaowan Nuclear Power and the State Nuclear Power Demonstration Power Station, they will bring millions of loads to the grid after commercial operation. Therefore, it will bring a lot of challenges to Jiaozhou Peninsula Regional Power Grid and even the whole provincial power grid.

With the development of nuclear power units, the completion and operation of any large capacity nuclear power units will bring a lot of impact on the regional power grid. Therefore, it is necessary to study the operation characteristics and peak regulation capacity of nuclear power units.

2. Operating characteristics of nuclear power
When the nuclear power unit is running at 50% ~ 100% rated power, its normal control mode is that the reactor power automatically tracks the change of turbine load. When the unit power output increases, the set value of unit power regulator (UPR) increases. In this way, the error between the set value and the actual power output will trigger the action of the speed regulator to increase the steam flow to the turbine and thus increase the electrical power output of the unit. Once the actual output power meets the requirements of the new set value, the speed regulator will maintain stable operation.
The increase of steam demand will lead to the decrease of steam generator pressure, and the error signal from steam generator pressure control (BPC) system will become the new set point signal of reactor regulation system (RRs). Then, the reactor regulation system will increase the reactor power until the steam generator pressure is restored and the unit reaches stable condition again. It can be seen that if the load requirements from the grid change, the result is a similar control response. In this case, the required setting value remains constant, and the error caused by load change will adjust the setting value of the speed regulator.

Shandong Haiyang nuclear power plant #1 is an imported AP1000 PWR unit, which belongs to the third generation advanced model. It adopts passive safety system, which can also guarantee the heat of the reactor under the condition of power loss and power loss, which greatly improves the safety of the reactor. The method of reactor reactivity control in Haiyang nuclear power plant mainly adopts the control rod inserted into the reactor core to absorb neutrons by adjusting the displacement of the control rod, so as to control the fission process. At the same time, it can also adjust the concentration of liquid boron in the reactor core and the inlet temperature of the core coolant to assist in the control of reactor reactivity.

Because of a series of advanced control and detection measures, such as using burnable poison to reasonably arrange the power distribution in the core, and realizing the real-time detection of the power distribution in the core, the AP1000 has excellent operation characteristics:

First of all, in terms of daily load tracking capability, the traditional PWR nuclear power unit has the capability of 12-3-6-3 at the 24-hour load distribution ratio, while the AP1000 has a better 18-2-2-2 capability, that is, 18-hour 100% rated power operation, power reduction from 100% rated power to 50% rated power at a linear speed within 2 hours, and maintain for 2 hours, and then increase at a linear speed of 2 hours Power to 100% rated power. In terms of load regulation speed, the load regulation rate of AP1000 is faster than that of conventional PWR nuclear power units [1].

Secondly, from the operating Pt diagram, the AP1000 has a wider power adjustment range, which can increase or decrease power linearly from 15% rated power to 100% rated power at a speed of about 5% rated power per minute. At the same time, it can also increase or decrease power in a jump mode with the amplitude of 10% rated power, and the maximum jump range can reach 20% rated power in 10 minutes.

Thirdly, in terms of the impact of load reduction on the reactor, the rapid power reduction system can ensure that the reactor does not shut down when the unit load is reduced by more than 50%, which greatly improves the safety of the reactor.

Since November 15, 2019, Haiyang Nuclear Power #1 unit officially supplies heat to surrounding residents. Haiyang Nuclear Power uses intermediate extraction steam for heating. This technology has been widely used in conventional thermal power plants. According to public reports, the existing heating area of Haiyang nuclear power plant is about 700000 m². According to the calculation of 50W / m², the heat load is 35MW, the high exhaust enthalpy is 2489kJ / kg, and the hydrophobic enthalpy is 329kJ / kg, which is equivalent to about 16t / h of extraction steam. The influence of the current extraction capacity on the load adjustment of the unit can be ignored. The existing literatures have calculated the operation of the AP1000 unit with heating extraction. On the premise of meeting the minimum cooling flow rate of the low-pressure cylinder and the range of the flow rate at the extraction port, the conclusion is drawn: The recommended load range of the unit is 42% ~ 88% of the rated load when the high pressure exhaust steam extraction is 1000t / h. The unit is equipped with heating extraction of 1000t/h, and the corresponding heat load is 600MW, which can meet the heating area of about 12million m² [2].

3. Analysis of peak regulation capability of nuclear power units
According to the relevant national policies, nuclear power units are supported to undertake basic load operation. However, with the increasingly tense situation of power grid peak load regulation, the demand for nuclear power units to participate in peak load regulation is increasingly urgent. At present, the existing solutions include the construction of pumped storage and other supporting flexible peak shaving power supply, and sending the remaining power through the grid. However, the construction investment
of pumped storage power station is huge, and a large number of construction is unrealistic. The large-scale export of nuclear energy is still limited by the insufficient power load. Therefore, it is still necessary to study the regulation characteristics of nuclear power units and explore the self-regulation capacity of the units.

According to statistics, most of the nuclear power units in operation in China belong to the second generation and the second generation of improved pressurized water reactor nuclear power units. They have a large range of power regulation capacity in design, and can track daily load to a certain extent and participate in peak load regulation of power system. Shandong Haiyang Nuclear Power #1 unit is an imported AP1000 pressurized water reactor unit. In terms of design and selection, it is designed to operate with basic load and can also be operated with peak load regulation. Theoretically speaking, PWR nuclear power unit can operate at low load due to its low steam parameters and no load limit for minimum stable combustion. From the technical implementation point of view, after receiving the output adjustment command, the reactor reaction rate can be controlled by adjusting the proportion of control rods inserted into the reactor. Shandong Haiyang Nuclear Power #1 unit has not yet had peak shaving experience, but it can learn from the peak shaving operation experience of a large number of PWR nuclear power units at home and abroad [3].

There are three ways for nuclear power units to participate in peak load regulation of power grid at home and abroad:

- **Annual peak**: Generally, 1 / 3 of the fuel rods of nuclear reactors need to be replaced every 12-18 months, which is equivalent to the completion of a power generation cycle. When the fuel rods are replaced, the reactor must be shut down. In the case of multiple nuclear power units, according to the annual operation characteristics of the local power grid, it is possible to reasonably arrange the single unit refueling schedule and extend the operation time to participate in the annual regulation of the local power grid. This method is the most simple and feasible way, and it is also the most commonly used method to participate in peak shaving. Specific to Shandong Power Grid, there is a load peak every summer, and it can participate in annual peak shaving by arranging refueling of nuclear power plants to avoid the summer peak period. However, there are only two nuclear power units in Shandong Province, so the regulation effect of this way on power grid is limited.

- **Weekly peak**: This peak regulation mode is based on the fact that the nuclear motor group does not participate in the daily peak regulation. The PWR nuclear motor group has the ability to operate with low load for a long time, so that it can continuously operate with low load in a certain period of time, so that the rest of the load space can be prioritized to other adjustable power sources, such as fire power, etc. Specific to Shandong Power Grid, this method can be used to let nuclear power units participate in peak load regulation during special periods such as Spring Festival every year.

- **Daily peak**: AP1000 units have excellent daily load tracking capability and load regulation rate in the first 90% of the life cycle, and can participate in the daily tracking load peak shaving of the power grid. However, this approach needs to fully consider the safety of the nuclear power unit itself, and also puts forward higher requirements for the coordinated control between the nuclear island and the conventional island. Foreign nuclear power units have a long time of daily load tracking operation experience. In China, except for special days such as Spring Festival, daily load tracking operation is relatively rare.

There are two limiting factors for peak load operation of nuclear power units, which are the loss of economic benefits and the limitation of safety constraints. The economy of nuclear power generating units participating in peak load regulation should consider that nuclear power participating in peak regulation will reduce the power generation capacity of nuclear power plant, affect the efficiency of nuclear power plant, and improve the average generation cost in operation period. On the other hand, peak shaving will reduce the fuel utilization efficiency of nuclear fission reaction and spent fuel reprocessing in the process of nuclear fuel cycle, and reduce the economy of nuclear power operation. Therefore, it is necessary to analyze and calculate the cost of nuclear power units participating in peak load regulation scientifically and comprehensively, and establish compensation mechanism. In terms of safety constraints, the first is to consider the significant political and social impact of nuclear safety
issues; the second is that the load regulation operation of nuclear power plant is limited by the core cycle life. Nuclear power units in the middle of the life cycle can adjust the load within the range of design parameters, while the regulation range of units in the later life period gradually becomes smaller or even completely lost. Therefore, the nuclear power unit participating in peak load regulation must meet the requirements of nuclear safety and fuel life and two conditions within the power regulation capacity of the unit. The water and thermal power regulation models in the existing mathematical models of optimal power system scheduling are not suitable for nuclear power units.

4. conclusion
1. The load regulation operation of nuclear power unit is limited by the fuel cycle life and the frequency of participating in peak load regulation. Therefore, the operation mode of nuclear power unit should be determined in strict accordance with the load regulation principle, and the peak load regulation should be avoided at the end of the life cycle. In the selection of peak regulation mode, annual peak regulation or weekly peak regulation should be the main mode. When the peak load regulation capacity of the power grid is really insufficient, it can be considered to let nuclear power units participate in daily peak regulation operation with daily load tracking mode of 18-2-2-2 and peak shaving depth of maximum 50% rated power.

2. Considering the adverse effect of high peak regulation frequency on the economic and safety of nuclear power plant, the number of nuclear power units participating in load tracking in power grid during the life period should be scientifically and reasonably planned and arranged, and the operation mode of nuclear power units should be limited.

3. Considering the continuous, frequent load tracking the safe and economical operation of nuclear power units produce adverse effect, should be to participate in the peakload annual plan for scientific and rational overall arrangement. Determine the annual peak load operation plan of nuclear power units in advance, balance the peak shaving times of different units in the continuous life cycle, and try to avoid the unreasonable situation that individual units frequently participate in peak shaving while other units operate with base load for a long time.

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