Innovation Control Strategy Simulation Research of Once-through Steam Generator

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Abstract. The new type of nuclear power plant adopts once-through steam generator (OTSG) which can supply steam to the turbine, control and operation of OTSG is different from the traditional natural circulation steam generator, the control strategy of the traditional natural circulation steam generator is not applicable to OTSG. In order to meet the demand of the general operation of the integrated reactor, the operation control of OTSG is put forward. The paper proposes a double const control strategy that the average temperature of the primary circuit coolant and the secondary circuit steam pressure are kept constant, also proposes a coordinated control strategy considering reactor and turbine as a whole. The control strategy is different the traditional control method. In order to verify the control strategy, simulation experiments are carried out in a full-scale simulator system. The simulation results show that the proposed control strategy of OTSG in integrated reactor to meet the load demand, also can effectively guarantee the dynamic characteristics of pressure steam generator and related parameters of OTSG.

1. Introduction

In order to reduce the volume of the reactor pressure vessel, an integrated reactor typically uses the once-through steam generator. The OTSG has a high load response characteristic, and outlet produces superheated steam that increases the thermal efficiency of the secondary circuit \([1, 2]\). However, the secondary side water capacity of the direct current steam generator is small, and the secondary circuit feed water passes through the secondary side of the heat transfer tube at a time. Steam pressure easily affected by feed water flow and steam flow. Moreover, the water level of the OTSG is difficult to measure. Generally, the feed water control system of the pressurized water reactor nuclear power plant is not suitable for the operation of the integrated reactor. These characteristics of the OTSG make the operational characteristics of the integrated reactor different from the operating characteristics of the ordinary pressurized water reactor \([2]\). Another reason is that the reactor design department only considers the reactor control, the turbine system design department only considers the turbine control in the traditional design control method, while the integrated reactor needs to comprehensively consider the reactor and turbine matching. The reference \([3]\) presented a coordination control scheme which is used to study the rapid load following characteristics of OTSG, the effects of main operating parameters related to stable operation of OTSG are investigated. The reference \([4]\) adopted novel fuzzy logic based coordinated control for multi-unit small modular reactor power control system. The
reference [5] researched integrated pressurized water reactor’s behavior prediction using machine learning. The reference [6] researched a decision-making method based on Bayesian optimization algorithm for small modular reactor. The reference [7] adopted the fuzzy logic theory to design the fuzzy controller and the PID controller including the reactor power control system, the pressurizer’s pressure control system, and the feed-water control system. The references [3-7] is also studies about the control method, but the existing problem is that the control of reactor and turbine can not be studied as an organic whole. In order to solve the technical problems, this paper considers the control strategy from the reactor and the turbine including control strategy and control thinking of OTSG and detail design of the control system. Therefore, it is necessary to study the operational control of the OTSG according to the overall operational requirements of the integrated reactor.

2. Control strategy and control thinking of OTSG

The steady-state operation control schemes of nuclear power plants mainly include constant coolant constant temperature operation scheme, coolant average temperature program-changed operation scheme, steam pressure constant operation scheme, and ideal steady-state programming (the average temperature of the primary circuit coolant and the secondary circuit steam pressure are kept constant) [8-10]. In order to make the operation performance of the integrated reactor nuclear power plant first and second loop systems and equipment in different operating areas more coordinated, this paper proposes a dual constant operation scheme for integrated reactor operation control. Ideal steady-state programming can retain the advantages of constant coolant average temperature operation and steam pressure constant operation scheme, and overcome the main shortcomings of each of the two operation schemes. It is beneficial to improve the operating conditions and operating environment of the first and second loop systems and equipment, and can greatly improve the operational reliability and safety of the nuclear power plant.

Aiming at the constant operation of the secondary circuit steam pressure of the IP200 nuclear power plant, as shown in Figure 1, the schematic diagram of the OTSG control system was designed. The control system block diagram is mainly composed of steam generator feed water flow control, steam emission control, steam turbine control, reactor power control, etc.

The steam generator feed water flow control generally adopts a cascade control strategy. The SG feed water flow control mainly includes the feed water valve control system and the feed water pump control system. The water supply valve control system uses steam pressure as the main control amount, and the steam flow rate and water supply amount as the auxiliary control amount. The feed pump control system mainly controls the differential pressure before and after the feed water valve to keep the pressure difference constant.

The steam emission control system is divided into the control of the opening and closing control valve and the continuous pressure control valve. The control strategy is if the secondary circuit steam overpressure occurs, quickly open the opening and closing control valve for the second circuit steam pressure relief. Then, the on-off valve is slowly closed according to the pressure setting value, and then the continuous flow control valve is used to control the minimum flow rate of the feed water and the steam pressure.

The steam turbine control system mainly controls the main engine speed, but if the steam pressure fluctuates greatly, it is not conducive to the operation of the secondary circuit system. At this time, the steam turbine control system participates in the OTSG pressure coordinated control. Its coordinated control scheme is that if the pressure is lower than the lowest limit of the steam pressure, the steam turbine control system will not control the steam turbine regulating valve. If the pressure is above the upper limit of the steam pressure, the turbine control system will slowly open the turbine regulator to reduce the steam pressure.

If the OTSG pressure is kept constant and the primary circuit and the second circuit power are matched, the reactor power control adopts the cascade control system design, which is divided into the main regulator circuit and the secondary regulation circuit, and the feed water flow rate as the feed forward amount. Main regulator selected primary coolant average temperature as the primary variable,
it is advantageously employed to eliminate temperature deviation PID controller. The secondary circuit is capable of quickly adjusting the internal disturbance and realizing the fast response reactor nuclear power tracking secondary circuit load, and adopts an immune P controller. It has a leading role and quickly overcomes the steam load disturbance, thus ensuring the balance of reactor nuclear power and steam load, and introduce the feed water flow as the feed forward amount to offset or reduce the impact caused by the steam load disturbance. The load matching and constant pressure of the OTSG and the reactor need to be coordinated by the reactor power regulation system and the OTSG feed water control system.

Figure 1. Automatic control system principle diagram of the IP200

3. Simulation models of OTSG
In order to study the proposed operation control strategy, an integrated full-scale nuclear power plant simulation system was verified and tested. The simulation system model is a mathematical model based on physical mechanism. Its mathematical model mainly includes reactor thermal hydraulic model, reactor core physical model, and second loop system model. The reactor thermal hydraulic model program uses Theatre. Its mathematical model and its solution process are characterized by high precision, saving computing resources, and meeting real-time simulation requirements. The model program calculates a two-phase, two-component formula consisting of five basic conservation equations. In other words, the mathematical model of IPWR is established using Theatre code which developed by a simulation corporation of GSE. The reactor core physical model uses a three-dimensional two-group neutron diffusion equation model with six sets of delayed neutrons, which can accurately reflect the time and space dynamic processes of neutrons and calculate the feedback of reactivity. The second-loop system model includes models for the main steam system, steam turbine, condenser, and water supply system. It uses GSE's JTopmeret to build a fluid network model. JTopmeret uses two-phase flow (gas, liquid), multi-component (N2, O2, H2, CO2, SO2, NOx, etc.), non-thermal equilibrium model, which is based on the basic principles of mass, momentum, energy conservation, etc.[10] The steam generator and reactor node division diagrams are shown in Figure 2. The Table1 is given the main parameters of IP200 and OTSG.
Table 1. Main parameters of IP200 and OTSG under rated power conditions [4]

| Parameters                          | Value       |
|------------------------------------|-------------|
| Core thermal power                 | 220MW       |
| Core inlet temperature             | 559.15K     |
| Core outlet temperature            | 591.15K     |
| Pressurizer pressure               | 15.0MPa     |
| Primary coolant mass flow rate     | 1225kg/s    |
| Feed-water mass flow rate          | 88.0kg/s    |
| Main feed-water temperature        | 373.15K     |
| Steam header mass flow rate        | 176.0kg/s   |
| Steam header pressure              | 3.0MPa      |
| Superheat degree of steam          | 25K         |
4. Simulation analysis

In order to verify the effect of the control strategy, we use a full-scale simulation system as the research platform, and add the steam generator control system of the new control strategy to the simulation program. By adding control interface variables, the control program based on the new control strategy can be switched to the original simulation control program. The main experiments are the conditions of rapid load increase, rapid load reduction, main engine speed shutoff, forced natural circulation, etc., as shown in Figures 3, 4, 5 and 6.

Figure 3 shows the power process curve from 25% to 100%. According to the figure, the water supply closely follows the change of steam flow and the delay is small. The nuclear power also has a small delay with the change of the feed water flow. The main steam pressure decreases with the opening pressure of the main valve, but it is not lower than 0.7, within the normal operating range of the direct current steam generator. The steam pressure is restored to 0.95 by the increase of system feed water and nuclear power regulation. At this time, the feed water pressure is continuously adjusted with the change of steam pressure. The steam generator superheat degree is greater than 1.0 in the whole process, which is higher than the design value of 0.9.

Figure 4 shows the process curve of power from 100% to 25%, which is exactly the opposite of the process of Figure 3. The water supply can follow the change of steam flow, and the nuclear power changes with the flow of feed water. The steam pressure increases as the main valve closes, but is much lower than the steam pressure of 1.3. The superheat is always greater than the design value of 0.9.

Due to the sudden closing of the main valve, the steam pressure rises rapidly, and the adjustment of the feed water regulating pump takes time, so a large decrease in the flow rate of the feed water occurs. After that, due to the opening of the discharge valve, the steam pressure drops, and the adjustment of the feedwater valve and the pump ensures that the feed water changes with the change of the steam flow. The nuclear power of the whole process changes with the flow of the feed water. In the 30 seconds after the speed is turned off, the superheat of the steam generator changes drastically and appears to be lower than the design running value for a short time, but the whole process still has a certain degree of superheat, which can also ensure the steam quality of the steam generator.

Figure 6 is the process curve of forced to natural circulation conditions. Due to the main pump stopping, the average temperature setting of the reactor under forced circulation conditions is higher than the natural circulation condition. This allows the power conditioning system to perform a rapid pressure bar at the beginning of the replacement to reduce the nuclear power. In the later period, due to overshoot, the stick was lifted and finally stabilized. This makes the steam generator superheat change, but the process has a certain degree of superheat. Mainly due to the large disturbance of steam load, the change of feed water flow, steam flow, steam pressure and feed water pressure is small in the whole process.

In short, the simulation strategy proposed in this paper can guarantee the operation of the integrated reactor OTSG through four kinds of typical working conditions simulations such as rapid load increase, fast load reduction, main engine speed shutoff and forced natural circulation.
Figure 3. (a) Simulation Curve of OTSG parameters while Inducing Nuclear Power

Figure 3. (b) Simulation Curve of OTSG parameters while Reducing Nuclear Power

Figure 5. (a) Simulation Curve of OTSG parameters while the Main Turbine Shutdown
5. Conclusions
In this paper, the operation control of OTSG in integrated reactor nuclear power plant is studied, and the operation control strategy suitable for OTSG is proposed and the corresponding control system is designed. The coordinated control of the relevant control system and the OTSG control system is also considered accordingly. In order to fully verify the control scheme proposed in this paper, the proposed controller is added to the full-scale simulation system. The simulation test results show that the proposed OTSG control strategy meets the requirements of the integrated reactor fast tracking load, and can effectively ensure the dynamic operating characteristics of the OTSG pressure and related parameters. It has certain reference significance for the actual control system design of OTSG pressure. However, in order to reach the practical stage, further technical verification and validation are needed, including software, hardware and control algorithm.

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