The Analysis and Simulation Study of the Control System for the Floating Nuclear Power Plant ACP100S

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Abstract: Floating nuclear power plant (FNPP) is built on the offshore platform. As a new way of using nuclear energy in the sea, floating nuclear power plant can be operated in a fixed area, but also can be moved to other areas to provide energy by self propulsion or by means of tugs. The FNPP can provide power supply, fresh water and high temperature steam and other products. So it can be used as special energy sources, such as regional power supply, district heating and offshore oil exploitation. Based on the market demand of floating nuclear power plant, China National Nuclear Corporation has developed different types of floating nuclear power plant. One of them, named ACP100S, was developed on the basis of the technology of land-based small modular reactor ACP100.In this paper, firstly, the general technical parameters and the overall technical scheme of ACP100S are briefly introduced. On the basis of this, the design scheme of the control system is discussed, and the difference of the system design is compared with that of the land based on the characteristics of the application environment. These differences include: tilt, swing and other marine environmental conditions on the impact of the design of the control system, influence of layout space changes brought to the overall design of the control system and the influence of the load following requirements for the control system under the circumstance that the FNPP is running on the sea in the isolate island state, etc. Finally, the simulation results of the control system are analyzed under several transient conditions. The results show that the optimized control scheme can meet the requirements of the floating nuclear power plant.

Keywords: Simulation, Control system, Floating nuclear plant

1 Introduction

A floating nuclear power plant is a special device for installing nuclear power plant on offshore platform and providing energy. Because of the flexibility of offshore platforms, the conditions for flexible deployment and use of nuclear energy in different regions are created, especially in the vast ocean area. Floating nuclear power plant (FNPP) can offer electricity, heat, water and steam and other products, which can meet the special energy supply area, district heating, offshore oil, chemical industry, or remote areas, islands and other needs. So it has the characteristics of strong flexibility and wide applications [1].

Because FNPPs operate in the marine environment, the operation of relevant systems and equipment design must take into account the impact of Marine operating environment. For the control system of floating nuclear power plants, there are some differences between the operational control requirements and the operational control requirements of the control systems of land-based nuclear power plants. This paper introduces the overall technical scheme of ACP100S floating nuclear power plant independently developed by China National Nuclear Corporation (CNNC). The control requirements of related control systems are analyzed, and the control scheme is described. On this basis, the simulation modeling study is carried out, and the simulation analysis results of the control system are given.

2 ACP100S floating nuclear power plant and its overall technical scheme

2.1 Research and development background

At present, the sole development of large NPPs is not meet with the extensive demands of the electricity in different regions and non-electricity applications. Therefore more and more countries are developing the advanced small and medium sized reactors (SMRs) to meet the more extensive requirements. According to the report made by IAEA[2], 13 SMRs are under construction in six countries and the approximately 45 innovative SMR concepts research for electricity generation and other applications is being carried out. FNPPs are also included in the SMR because of their low level of power[3].

Compared with large-scale land-based nuclear power plants (NPPs), floating nuclear power plants have the following characteristics:

- Better mobility,
- Can be built in most coastal areas,
- May be built in batches according to energy needs,
- Land area is not occupied,
- Infrastructure can be simplified.

In China, with the development of marine resources, more and more energy requirements are needed, and the long-term and stability requirements have been put forward. In this case, the floating nuclear power plant has become a good choice. As a result, CNNC has developed several types of FNPPs, using existing pressurized water reactor technology, combined with the R & D results of land-based SMRs. Among them, the ACP100S floating nuclear power plant is developed by using the technology results of CNNC ACP100[4] land-based small reactor.

2.2 ACP100S overall technical scheme

Considering the space condition and the marine environment condition, compared with ACP100, ACP100S has improved the security system, reactivity control mode and some equipment configuration. The main technical features of ACP100S are as follows:

- Integrated layout of primary system and equipment. So the large LOCA is eliminated.
- Small radioactivity storage quantity.
- The ship hull is used as the carrier of the FNPP reactor. The marine environment characteristics are fully considered, so the seawater is used as the final heat sink, and the safety systems combining active and passive are adopted.
- The reactor core is below the waterline of the ship, so the long-term residual heat can be removed passively in the case of blackout for the whole ship.
- Reactivity control uses control rod and solid burnable poison to reduce wastewater discharge.
- With modular design concepts, one or more ACP100S modules can be used in a FNPP to meet different power requirements.

The main technical parameters of the ACP100S floating nuclear power plant using a single reactor are shown in Table 1.

Table 1 The main technical parameters of the ACP100S

Parameter	Value/Type
Thermal power	310 MW
Electrical power	~100 MW
Reactor layout	Integrated
Refueling period	2 Years
Coolant average temperature	303 ℃
Operation pressure	15 MPa
Fuel assembly number	57
Reactivity control method	Control rod and solid burnable poison
Steam generator type	OTSG
Main steam pressure	4 MPa
Safety system	Active and passive
Plant carrier form	Double bottom and double hull ship
Hull displacement	40000 t

3 ACP100S Control system scheme

3.1 Overall control requirement analysis

The control systems of ACP100S include the control systems of the nuclear steam supply system (NSSS) and the control systems of the conventional island. This paper mainly describes the NSSS control systems. According to the characteristics of ACP100S, such as integrated reactor, internal once through steam generator, and operation at sea, the NSSS control systems of ACP100S should meet the following design requirements:

a. Due to the requirement of the minimum stable operation power of the OTSG, the automatic control range of the reactor power control and feed water control system is 20%Full Power(FP)-100%FP.
b. According to the static running characteristics of ACP100S, the primary control principle is to maintain the main steam pressure at a constant and the reactor coolant average temperature at a constant during the load following. When subjected to external disturbances, the control system shall automatically return the nuclear power plant to a stable equilibrium state.
c. Because the FNPP is generally used for the power supply of offshore oil and gas platforms, the power grid is usually in an isolated island state. Therefore, the nuclear power plant is required to

have better load following capability. The control system should be able to make nuclear power plant to withstand the following load change without triggering the protective action of the system: step load change (±10%FP step), the linear load change (considering ±5%FP/min gentle condition and 30%FP/min more severe condition) and load rejection.

d. Floating nuclear power plants can be operated by a single reactor or multiple reactors to meet the needs of different users. In the operation of multiple reactors, if there is a joint operation between the secondary loop systems of different reactors, then the coordinated control system should be considered in the overall design of the control system. During the FNPP operation, the coordinated control system plays the total scheduling functions in two reactors and the turbine generator with sending coordinated control command to related control systems. On the one hand, it causes the reactor power to track the turbine load; on the other hand, it can restrain the impact of the load jump on the reactor. Each reactor is operated in accordance with the target load allocated by the coordinated control system to prevent the occurrence of "grab load".
e. Considering the marine environment conditions, the control system and its equipment should adapt to the conditions of sea conditions such as tilt, sway, shock and jolt (the specific values should be considered according to different sea conditions). Salt mist and mildew should also be considered.
f. The control system should be integrated and miniaturized as a result of the limitation of the space of the offshore platform.

3.2 Composition and preliminary scheme of NSSS control system

3.2.1 Reactor average temperature control system

The main function of the reactor average temperature control system is to control the power of the reactor by regulating the average temperature of the reactor coolant, and guarantee the normal power generation of the FNPP according to the load demand. When a FNPP is in steady state operation, the system keeps the average temperature of the reactor at the set-point. Under transient conditions, it achieves automatic control of load variations within specified limits without causing reactor emergency shutdown or steam discharge.

The reactor average temperature control system includes two control channels: the temperature channel and the power mismatch channel. The temperature channel receives the average temperature measurement computed from the core inlet and outlet temperature measurements, and compares it with the reference temperature (a fixed value). The error between the reference temperature and the measurement temperature is the primary control signal of the system. The power mismatch channel is a forward channel. This channel receives the nuclear power signal and the total feedwater flow of the secondary side. The error of these two signals is added to the temperature error signal. The final error signal is processed by the rod speed program which produces the control rod travel speed signal and two direction logic signals. The schematic diagram of the reactor average temperature control system is shown in Fig.1.

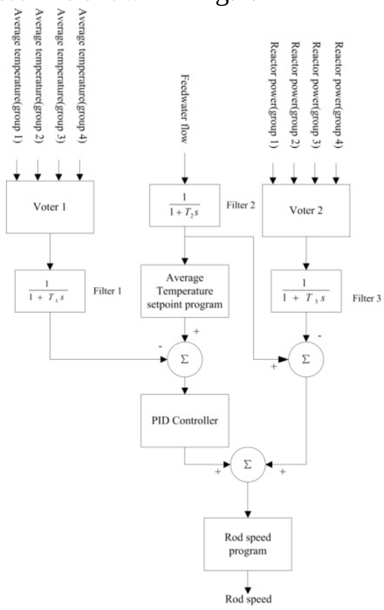

Fig.1 The control scheme of the reactor average temperature control system

3.2.2 Pressurizer pressure and water level control system

The function of the pressurizer pressure control system is to ensure that the reactor coolant system pressure is maintained in the setting value during normal operation. The emergency shutdown of the reactor will not result in the transient condition and will not cause the safety valve to act. The function of the pressurizer water level control is to maintain the pressurizer water level in the specified limits, to keep the coolant system has a certain amount of coolant in steady and transient normal circumstances. The control principle of the pressurizer pressure control system is to compare the measured pressure value with the set-point. If the error exceeds the threshold, the valve and electric heater action of the trigger will be triggered. The control principle of pressurizer water level control system is to compare the measured value of water level of pressurizer and its fixed value. If the error exceeds the threshold, the corresponding valve and pump action will be triggered. The control principles of these two systems are relatively simple, so the control principle diagram is not given here.

3.2.3 Steam generator feedwater control system

The function of the Steam generator (SG) feedwater control system is to maintain a fixed value of the SG secondary side pressure and make the feedwater flow accommodate the load requirements by regulating the feedwater flow into the OTSG.

During 0 to 20%FP, the feedwater flow is controlled by manual. The bypass control valves are used to adjust the feedwater flow to the steam generator manually through the startup feedwater line and the startup feedwater pump. During the 20%FP to 100%FP, the feedwater flow is regulated automatically through the main feedwater pump, main feedwater control valve and the main feedwater line. The bypass feedwater channel is not operation at this condition.

The automatic control of the feedwater flow is accomplished by the main feedwater flow control valve in conjunction with the feedwater pump speed control. The three-element feedwater controller regulates the main valve opening by continuously comparing the steam pressure signal, the feedwater flow signal and the steam flow signal.

The control scheme of the feedwater valve controller is shown as in Fig.2. The control scheme of the feedwater pump controller is shown as in Fig.3. The symbol '△P' in the Fig.3 represents the inlet and outlet differential pressure of the feed valve.

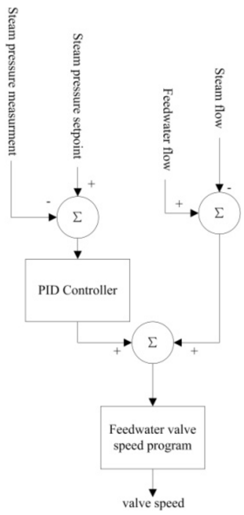

Fig.2The control scheme of the feedwater valve

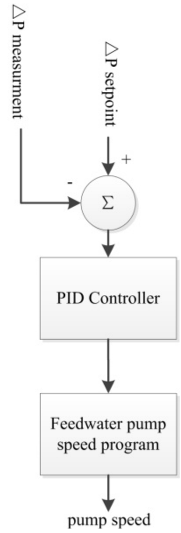

Fig.3 The control scheme of the feedwater pump

3.2.4 Steam dump control system

The function of the steam dump control system is as follows: when the reactor power and secondary loop load are different, the excess steam is dumped to the condenser. This prevents the temperature and pressure in the nuclear steam supply system from exceeding the protection threshold, thereby ensuring the safety of the FNPP. According to the secondary loop system and safety system settings of ACP100S, the steam dump control system is divided into high pressure dump control channel and power difference dump control channel.

In the 20%FP~100%FP range, when the turbine load appears to be greater than the step change of 10%FP, the power difference dump control channel implements control based on the difference between the nuclear power signal and the turbine load signal. The steam pressure dump control channel implements control according to the deviation between the measured steam pressure signal and the high limit set-point value of the steam pressure. These two dump control channels all have regulated dump patterns and fast open dump patterns.

The control scheme of steam dump control system is shown in Fig.4

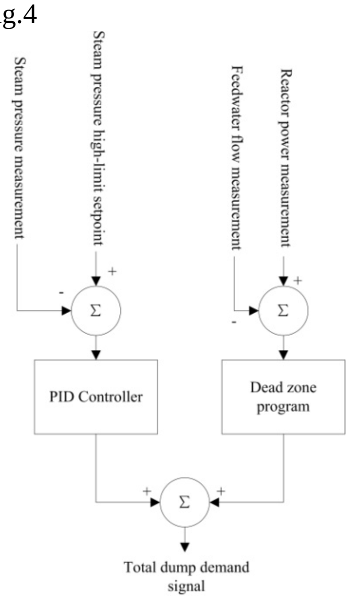

Fig.4 The control scheme of the steam dump control system

4 Control system simulation study

4.1 Modeling of controlled object and control system

The scheme of ACP100S control system is validated and optimized by numerical simulation. In order to achieve good simulation results, closed loop simulation technology is adopted. The controlled object is modeled by the best estimation program RELAP5, and the control system is modeled by MATLAB/SIMULINK program. Data exchange between the two programs is carried out using a database. The synchronization between two simulation programs is realized by synchronization mechanism on the simulation workstation. A description of the reactor modeling is given below.

The modeling of the reactor includes the reactor pressure vessel, the falling section, the lower chamber, the core active region, the by-pass channel, the upper chamber, etc. The reactor modeling node partitioning is shown in Fig. 5.

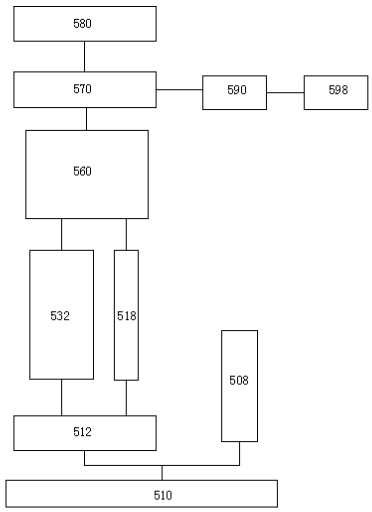

Fig.5 Reactor modeling node diagram

As shown in Fig. 5, the coolant flowing out of the reactor coolant pump enters the lower end of the pressure vessel (node No.510) through the descending section (node No.508) and flows to the next part through the reactor core barrel (node No. 512). The core portion has only one channel, but is divided into three segments along the height direction. The coolant collects again after passing through the core and the bypass channel. Then it then flows through the core part of ascent (node No.560) and the upper water outlet section of hanging basket component (node No.570), into the upper chamber pressure vessel area (node 580) and steam generator (OTSG) primary side of the front intake part (node No. 590 and 598).

4.2 Simulation verification

4.2.1 Control system acceptance criteria

According to the ACP100S control system requirements, the control system should meet at least the following technical indexes:

a. The stable quality of the reactor temperature control system: the steady-state error of the reactor power is less than±2% rated power and the steady-state error of the average temperature is less than ±1.5℃.
b. Steam generator feedwater control system: the steady error of the steam pressure is less than ±0.2MPa.
c. In the process of lifting load and load reduction, the overshoot of the controlled quantity of the above two control systems is not more than 10%.

In addition to meeting the above technical specifications, in the normal transient conditions, the control system must meet the following acceptance criteria:

- Reactor protection actions are not permitted，
- Except the load rejection condition, the steam by-pass valve action is not allowed,
- The action of the pressurizer relief valve is not permitted,
- Secondary loop parameter quality meets steam requirement.

The following conditions of load step change and load rejection are taken as examples to illustrate the simulation results of the control system.

4.2.2 Load step change condition

Fig. 6 (a) to Fig. 6(c) gives the simulation curves of the related parameters when the load step change from 100%FP to 90%FP.

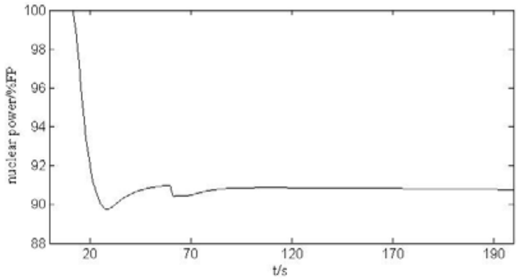

Fig.6 (a) The curve of the nuclear power

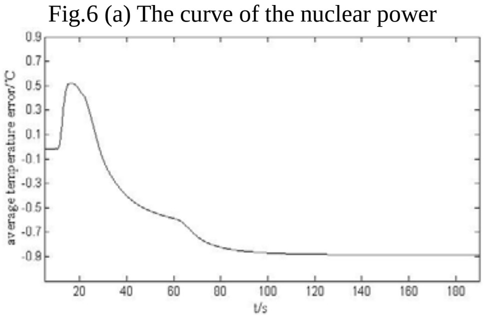

Fig.6 (b) The curve of the average temperature error

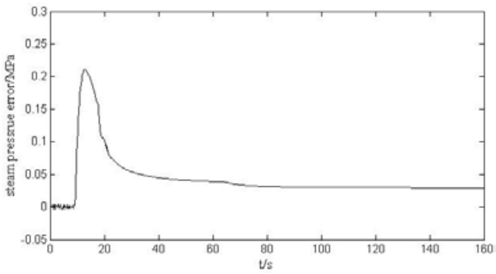

Fig.6(c) The curve of the steam pressure error

Fig. 7 (a) to Fig. 7(c) gives the simulation curves of the related parameters when the load step change from 90%FP to 100%FP.

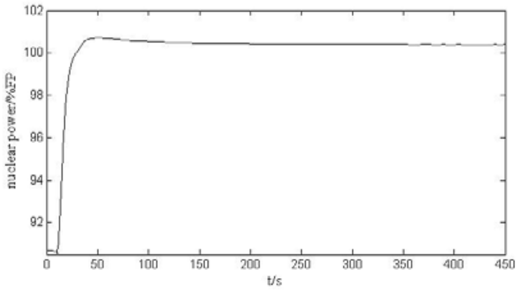

Fig.7 (a) The curve of the nuclear power

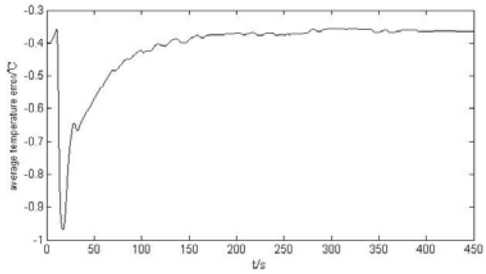

Fig.7 (b) The curve of the average temperature error

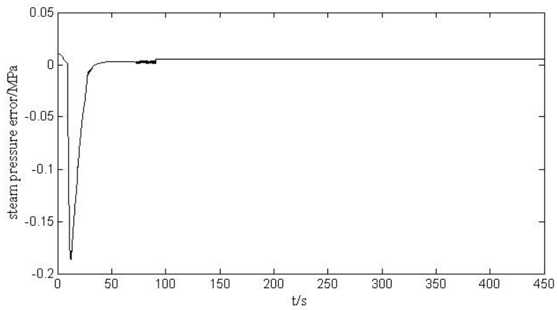

Fig.7(c) The curve of the steam pressure error

Seen from Fig.6 (a) to Fig.6(c),the simulation results show that in the early transient load step down, due to a sudden decrease in steam consumption, makes primary loop and secondary loop energy is out of balance, which leads to the secondary loop steam pressure rises rapidly. The average temperature of the reactor coolant rises slightly due to the large inertia of the primary loop. Subsequently, under the influence of the control system, the power of the reactor begins to decrease, and the temperature and pressure of the primary loop decreases. With the stability of the reactor power, the temperature and pressure of the primary loop and the secondary loop gradually stabilize. The simulation results of Fig. 7 (a) to Fig. 7 (c) show that the change of relative parameters during load step up is the opposite.

The simulation results of the load step change show that the transient and steady state indexes of the main parameters meet the acceptance criteria under this condition, and the control system achieves the desired design results.

4.2.2 Load rejection condition

The load rejection mode is load rejection from 100%FP to 20%FP, and the simulation curves of relative parameters are shown in Fig.8 (a) to Fig.8 (c).

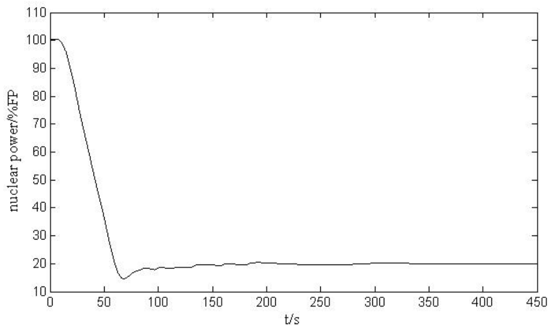

Fig.8 (a) The curve of the nuclear power

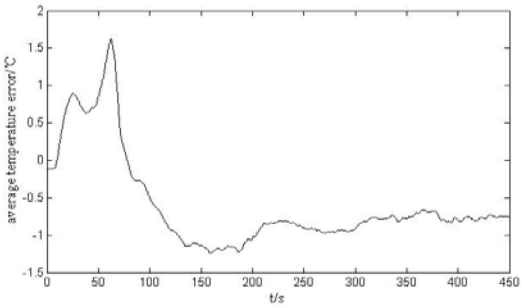

Fig.8 (b) The curve of the average temperature error

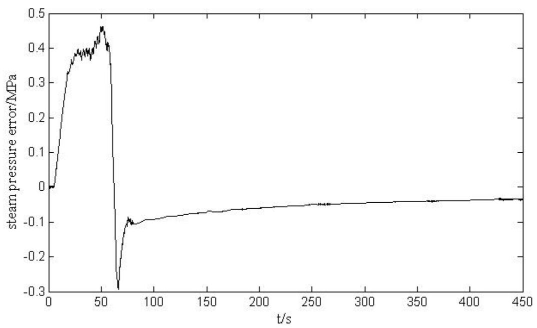

Fig.8(c) The curve of the steam pressure error

At the beginning of the load rejection transient, the turbine inlet valve closes rapidly, and the steam flow decreases rapidly in a very short time. No matter how to control the flow rate of water supply by automatic control or manual constant speed, the feed water flow control system cannot match the feed water flow with the steam flow in such a short time. It makes the volume of OTSG secondary side flow accumulate rapidly, and the ability to take away energy from the primary side decreases rapidly, resulting in a great change in the temperature and pressure of the primary loop and the secondary loop. The secondary loop steam pressure rises rapidly to the discharge threshold, causing the steam to discharge, and the overshoot of the steam pressure then reaches its peak value. With the action of primary and secondary loop control systems, the power of the reactor decreases and the feed water flow and the steam flow gradually became balanced. Although the steam dump valve is closed so that the steam pressure fluctuations, but the general trend is gradually stabilized, and achieve the new stable operation condition. As can be seen from the above simulation curves, in the load rejection transient process, the steady-state error and overshoot of the related parameters meet the requirements of the control index, and illustrate the effectiveness of the control system design.

5. Conclusions

ACP100S is a floating nuclear powered device developed on the basis of the CNNC land based small modular reactor technology, which can be used for offshore energy supply. The design of control system must meet the requirements of ACP100S operation and control. Based on the introduction of the overall technical scheme of ACP100S, the requirements of the control system are analyzed, and the main control system composition and control scheme are introduced in the paper. The simulation analysis of the control system shows that the control system designed in this paper can meet the requirements of the relevant functional performance, and can be used as the basis of control system design for ACP100S floating nuclear power plant in the engineering design phase.

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