

Simulation and research on control methods for the secondary system of civil nuclear power ship

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Abstract

Secondary system, also known as steam power system, is an important part of the pressurized-water reactor nuclear power plant for ships. It's an effective method to improve reliability and operating safety of secondary system that researching on control methods for the secondary system of civil nuclear power ship. In this paper, the secondary loop system of civil nuclear power ship is taken as the research object, and the mathematical model of the concentrated parameter of steam generator is established. These mathematical models of secondary system are simulated in Simulink platform. The correctness of these mathematical models are verified by dynamic characteristics for each device under different conditions. The steam generator liquid level control system was designed by PID control method. Through the research on the system control method in the second loop, optimizing the automatic control degree of the second loop system is of great significance for improving the ease of use and safety of the nuclear power plant on civil ships.

Keywords: civil ship, nuclear power, secondary system, PID control method

1. Introduction

This paper focuses on the control methods of the secondary system of nuclear power plant of ships based on the application of civilian nuclear-powered ships [1][2]. According to the characteristics of the secondary system of the nuclear power plant, the mathematical model is established and the simulation control research is carried out [3].

(1) Combining the structure and characteristics of the secondary system of the nuclear power plant, establish a mathematical model of the concentrated parameters of the steam generator.

(2) According to the established mathematical model, simulate the dynamic change characteristics of the steam generator liquid level [4] under different power (5%, 15%, 30%, 50%, 100%) water flow step change experiment, observe the changes of dynamic characteristics of each part, to verify that the mathematical model is available.

(3) Based on the principle of PID control [5], the steam generator liquid level control system [6] in the secondary system of nuclear power plant is simulated, and the control results of load step reduction of each system under rated conditions are analyzed [7].

(4) For the phenomenon of "false liquid level" in the steam generator, PID control can not adjust the liquid level change well, and design the steam generator liquid level control system based on feedforward-feedback cascade control [8], by introducing steam flow as a feedforward control signal, it can offset the adverse effects of "false liquid level" on system control, and simulate the liquid level control when the steam load steps down under rated conditions.

* Manuscript received May 6, 2020; revised December 7, 2020.

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doi: 10.12720/sgce.10.1.44-50

2. Steam Generator Mathematical Model

The steam generator has complex nonlinear characteristics [9]. There are also many mathematical models of steam generators based on mass, energy conservation equations or thermal experiments [10], including nonlinear differential equations and transfer function models. This paper applies a segmented linear liquid level model of a steam generator designed by E. Irving:

$$H(s) = \left(\frac{G_1}{s} - \frac{G_2}{(1+\tau_2 s)} \right) (Q_w(s) - Q_s(s)) + \frac{G_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} + s^2} Q_w(s) \quad (1)$$

Where H is the steam generator level, S is the Laplacian, τ_1 、 τ_2 is the time delay, and G_1 、 G_2 、 G_3 is the positive constant, T is the oscillation period, Q_s is the steam flow, and Q_w is the feed water flow.

Where $\frac{G_1}{s}$ represents the volume effect, which is caused by the change in the quality of the steam outflow and feed water in the steam generator; $-\frac{G_2}{(1+\tau_2 s)}$ represents the change of liquid level. The size and quantity of bubbles below the liquid level change due to the change of steam flow and the flow rate of feed water in the steam generator; $\frac{G_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} + s^2}$ is the liquid level oscillation caused by the water supply in the descending channel.

The piecewise linear model integrates multiple linear models and integrates different linear models near different power operating points. The parameter G_2 , G_3 , τ_1 , τ_2 , T in the equation varies with different powers. The values of the parameters at 5%, 15%, 30%, 50% and 100% of the rated power points are shown in Table 1. It is believed that these parameters vary linearly between these power points.

Table 1. Liquid level model parameters

parameter	power (P) %				
	5	15	30	50	100
G_1	0.058	0.058	0.058	0.058	0.058
G_2	9.63	4.46	1.83	1.05	0.47
G_3	0.181	0.226	0.310	0.215	0.105
τ_1	41.9	26.3	43.4	34.8	28.6
τ_2	48.4	21.5	4.5	3.6	3.4
T	119.6	60.5	17.7	14.2	11.7
Q_w (kg/s)	57.4	180.8	381.7	660	1435

3. Simulation of Dynamic Characteristics of Steam Generator Liquid Level

According to the simplified mathematical model of the steam generator liquid level, the liquid level height depends only on the steam flow rate and the feed water flow rate. According to the transfer function of the feed water flow rate and the steam flow rate between the liquid level height, the influence

of the feed water flow rate and the steam flow rate on the liquid level height is constructed. The liquid level variation characteristics of the steam generator are studied under the condition that the feed water temperature and pressure are constant, the feed water flow and the steam flow respectively occur in a positive unit step change. The steam generator liquid level simulation model is established according to the parameters of the steam generator mathematical model. Fig. 1 shows the steam generator level Simulink simulation model when the feed water flow step is increased by 20kg/s under 5% power conditions.

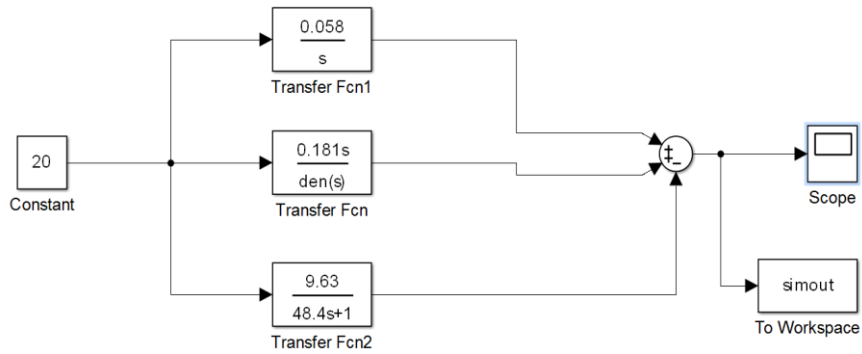


Fig. 1. Simulation model of steam generator liquid level at 5% power

Fig. 2 shows the change trend of the steam generator liquid level in the feed water flow step by 20kg/s under different powers (5%, 15%, 30%, 50%, 100%). The ordinate data in the figure is not the actual value, which is the relative ratio of the actual value to the rated value. Since the newly added feed water temperature is lower than the saturation temperature in the steam generator, when the feed water flow rate increases, the rapid heat absorption of the feed water causes the amounts of bubbles in the steam generator to decrease, the liquid level height decreases, and a "false liquid level" phenomenon occurs.

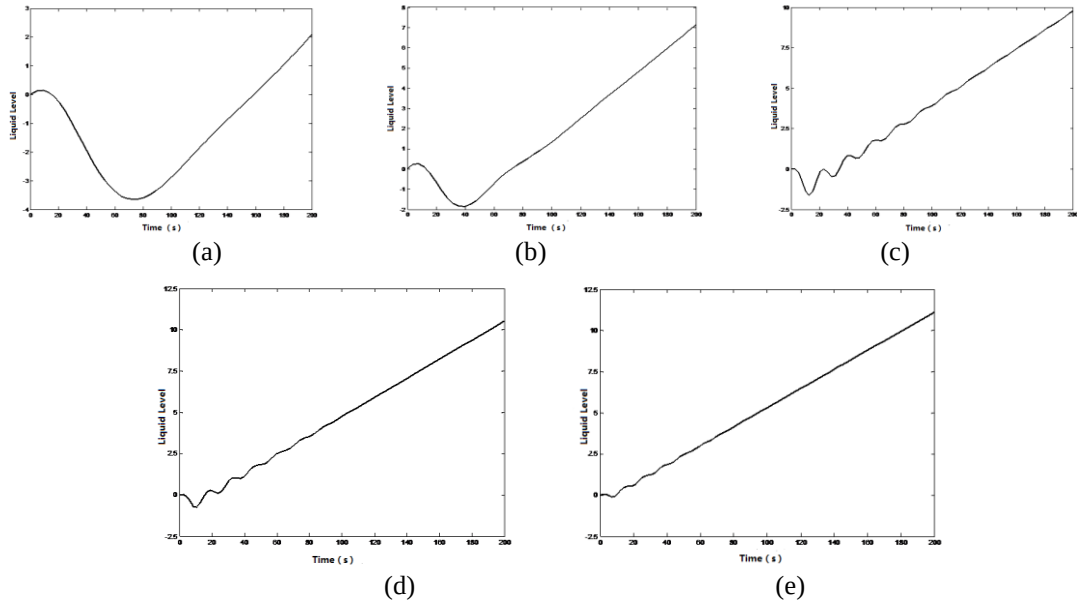


Fig. 2. Dynamic response of the steam generator level at a step change of feed water flow power: (a) 5%, (b) 15%, (c) 30%, (d) 50%, (e) 100%.

Fig. 3 shows the dynamic response of the steam generator level at a steam flow step increase of 20 kg/s at different powers (5%, 15%, 30%, 50%, 100%). The vapor phase pressure in the steam generator decreases with the increase of the steam flow rate, enhances the vaporization intensity, and the volume of the bubble on the liquid surface becomes larger, resulting in an increase in the liquid level of the steam generator, thus causing a false liquid level phenomenon.

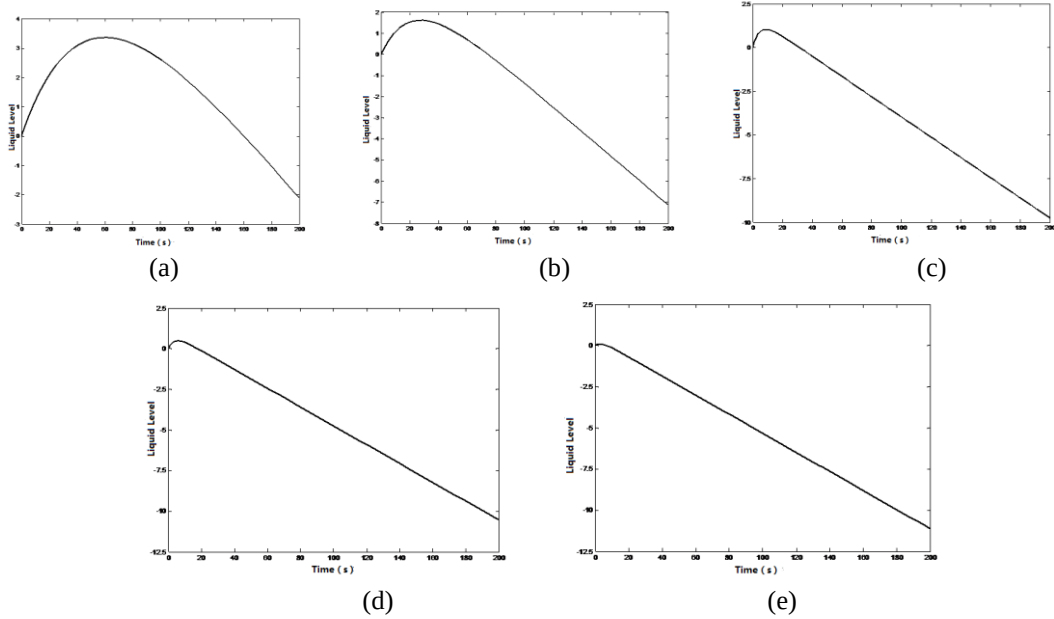


Fig. 3. Dynamic response of the steam generator level at a step change of steam flow power: (a) 5%, (b) 15%, (c) 30%, (d) 50%, (e) 100%.

According to the change of the liquid level of the steam generator, the influence of the feed water flow rate and the steam flow step change on the height change and duration of the "false liquid level" under different power conditions is different. The lower the reactor power, the longer the "false liquid level" height change and the influence time caused by the step change of the feed water flow and the steam flow rate.

4. PID-based Steam Generator Liquid Level Control Simulation

The control of the feed water flow according to the liquid level deviation, that is, the single impulse liquid level PID adjustment method, the closed loop control is applied on the basis of the steam generator simulation model to realize the PID control of the steam generator liquid level. The steam generator liquid level control simulation model is established in Simulink. The simulation block diagram is shown in Fig. 4.

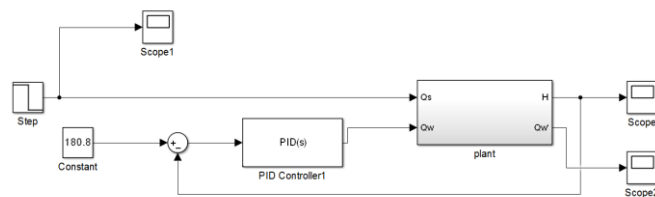


Fig. 4. Simulation model of steam generator level control system

The design operation conditions are as follows: the steam generator is stable under 15% power conditions before 150s, and the steam load step is reduced by 20% at 150s, it is reduced by 36.2kg/s. As shown in Fig. 5 (a) . The PID controller parameter setting values are 2.10, 0.30, 0. Figs. 5 (b) and (c) show the change of feed water flow and liquid level with time under PID control mode.

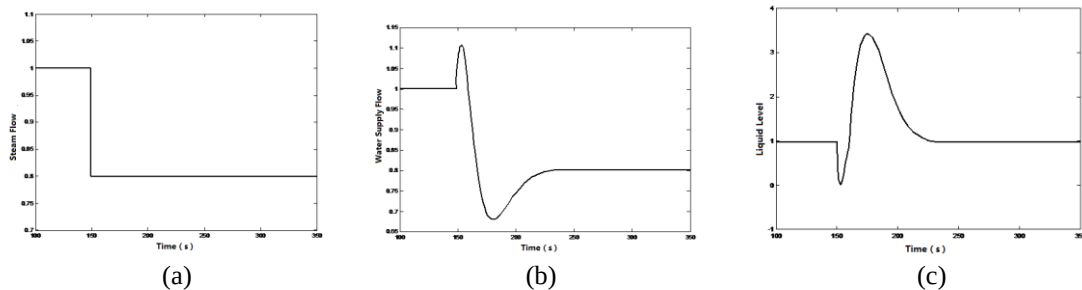


Fig. 5.(a)Variation of steam flow over time,(b) PID control scheme steam generator feed water flow change,(c) PID control scheme steam generator level change

According to the simulation results, in the PID control mode, there is a “false liquid level” in the steam generator, causing the feed water valve to malfunction, and the feed water flow to increase in a short time after the steam flow rate drops. In the single PID liquid level control system, the feedforward control is added, and the steam flow change is used as the feedforward signal, which can offset the adverse effects caused by the “false liquid level” .The block diagram of the simulation model is shown in Fig. 6.

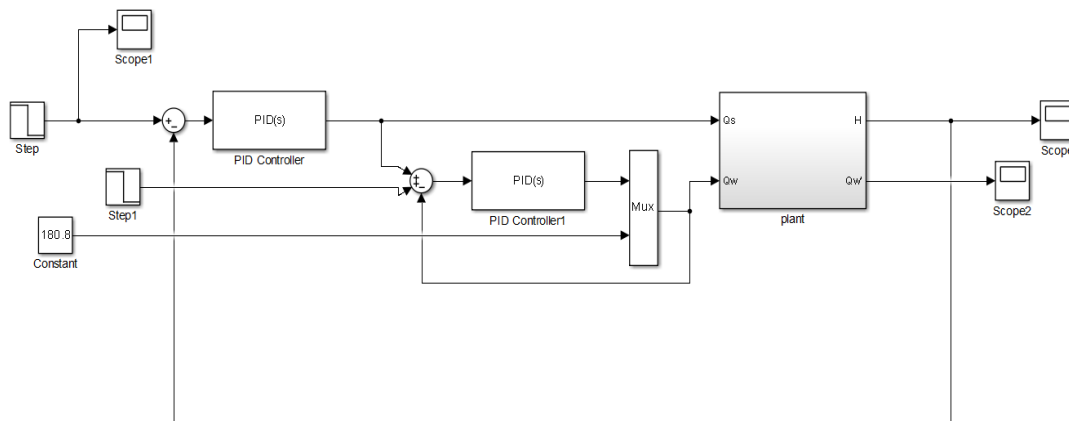


Fig. 6. Simulation model of steam generator level feedforward cascade control system

The feed water flow change and liquid level change in the steam generator liquid level control system is based on the feedforward-feedback cascade control system. The main controller and the sub-controller use PI controller. The main controller parameter setting values are 2.80, 0.50, 0, and the sub-controller parameter setting values are 1.20, 0.80, 0. The trend is shown in Figs. 7.

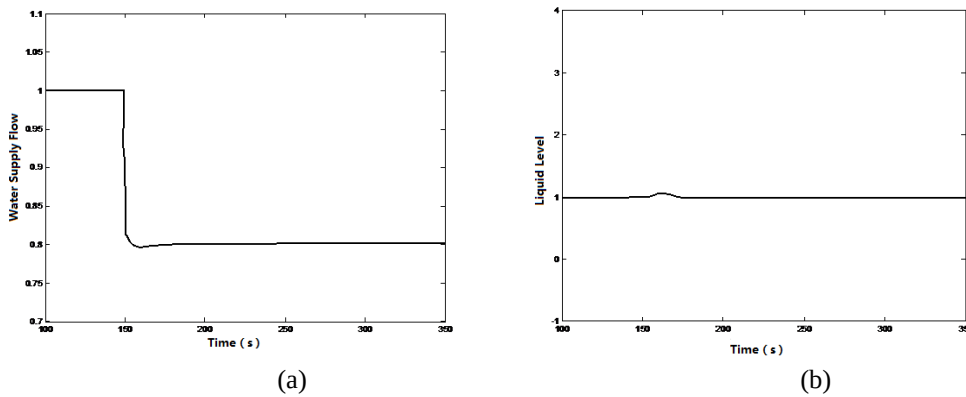


Fig. 7. (a)Feed water flow rate changes with time, (b) Steam generator level changes with time.

Compared with the single PID control, the feed water flow in the feedforward-feedback cascade control mode can quickly track the change of steam flow, and has good dynamic characteristics such as small overshoot and short adjustment time, and is almost free from "false liquid."

5. Conclusion

The secondary system control for civil nuclear-powered ships with application prospects is studied in this paper. According to the characteristics of the secondary system of the nuclear power plant, the mathematical model is established and the simulation control research is carried out.

(1)According to the simulation results, the "false liquid level" phenomenon of the steam generator is more serious under low load conditions, and the liquid level transition time is longer under the same disturbance.

(2)The simulation test is carried out under the condition of load change. The control effect of the steam generator liquid level PID control system is poor, and the liquid level change cannot be well adjusted;

(3)Due to the instantaneous "false liquid level" phenomenon in the steam generator when the steam flow changes with the load, the PID control cannot adjust the liquid level change very well.

(4)The steam generator liquid level control system based on feedforward-feedback cascade control simulates the liquid level control when the steam load steps down. The result shows that the feedforward-feedback cascade control system has a short adjustment time for the liquid level, and the dynamic characteristics are good.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Li Xu conducted the research; Xiong Zheng, Li Xu, Yang Fang and Junting Fang analyzed the data; Xiong Zheng, Li Xu and Yang Fang wrote the paper; Li Xu reviewed the paper; all authors had approved the final version.

Acknowledgements

The work was financially supported by the national high technology research and development program (863 Program) (2012AA112701).

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