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Original Article

Design of digital nuclear power small reactor once-through steam generator control system

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ABSTRACT

The once-through steam generator used in the small modular reactor needs to consider the stability of the outlet steam pressure and steam superheat of the secondary circuit to achieve better operating efficiency. For this reason, this paper designs a controllable operation scheme for the steam pressure and superheat of the small reactor once-through steam generator. On this basis, designs a variable universe fuzzy controller, first, design the fuzzy control rules to make the controller adjust the PI controller parameters according to the change of the error; secondly, use the domain adjustment factor to further subdivide the input and output domain of the fuzzy controller according to the change of the error, to improve the system control performance. The simulation results show that the operation scheme proposed in this paper have better system performance than the original scheme of the small reactor system, and controller proposed in this paper have better control performance than traditional PI controller and fuzzy PI controller, what's more, the designed control system also showed better anti-disturbance performance in lifting experiment between 100% and 80% working conditions. Finally, the experimental platform formed by connecting the digital small reactor with Matlab/Simulink through OPC(OLE for Process Control) communication technology also verified the feasibility of the proposed scheme.

1. Introduction

Small modular reactor have greatly improved the safety of nuclear power due to their modular structural design, and have now attracted more and more attention from scholars. The schematic diagram of the small modular reactor is shown in Fig. 1. As an important heat exchange device connecting the primary and secondary circuits of small modular reactor, the outlet pressure and superheated steam temperature are directly affects the heat exchange efficiency of the once-through steam generator, and then affects the economic operation of the small reactor. Therefore, the control research on the once-through steam generator is of great significance [1,2].

At present, the research on the control scheme of the once-through steam generator mainly focuses on the control of the outlet steam pressure of the second circuit of the once-through steam generator [3–5]. But in the process of lifting and lowering the load, if only the steam pressure at the outlet of the once-through steam generator is controlled, the steam superheat fluctuates greatly, which has an impact on the stability of the secondary circuit equipment and the system [6], and if only the steam pressure is controlled, the steam superheat changes have occurred, making it impossible to determine whether the electric power rate when reaching the steady state matches the load setting value [7–9]. In this case, this paper discusses and designs a bistable operation scheme for the steam pressure and superheat of the once-through steam generator.

In industrial control, because the controlled object is often accompanied by nonlinear and time-varying characteristics, it is difficult to establish an accurate mathematical model of the controlled object or the mathematical model is too complicated [10–12]. in order to overcome the problem that the controller relies too much on the mathematical model of the controlled object, fuzzy control has its advantages in industrial control because of its characteristic of not relying on the mathematical model of the controlled object [13,14], but generally the quantization factor and

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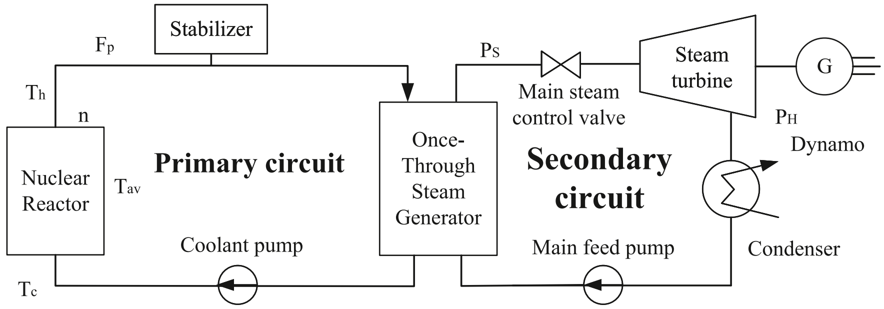

Fig. 1. The schematic diagram of the small modular reactor.

scale factor of the fuzzy controller are fixed values. When the error of the controlled system is gradually reduced, the adjustment range of its domain is still the adjustment range of the initial domain. If the error is too small, it is difficult for the initial domain to meet the control accuracy required by the system, although it can be increased by adding fuzzy rules [15,16]. To subdivide the fuzzy domain, but the increase in the number of rules virtually increases the amount of calculation and affects the real-time control.

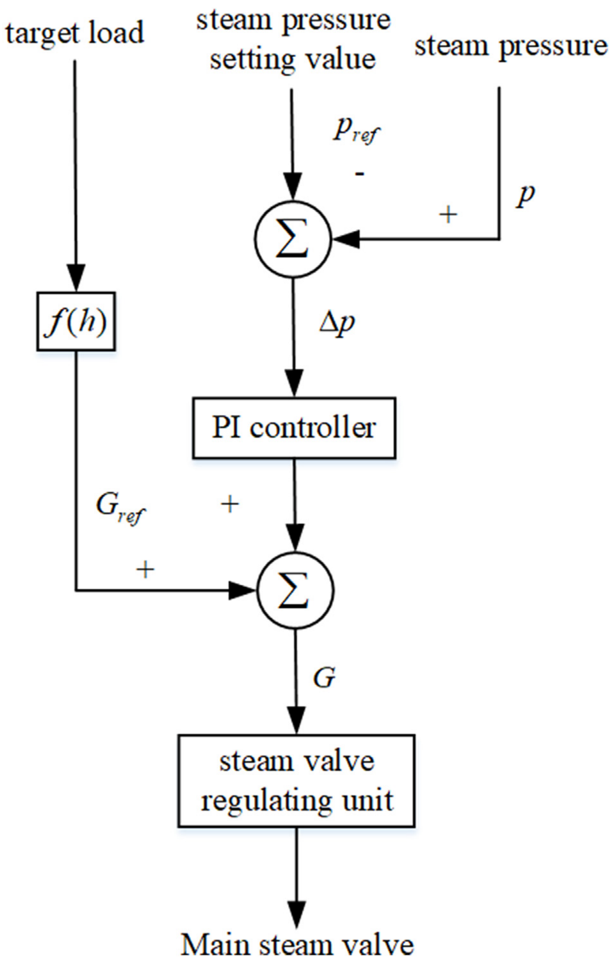

Fig. 2. Schematic diagram of steam pressure control of once-through steam generator.

Therefore, this article adopts the idea of changing the domain of fuzzy controller, uses the expansion factor to adjust the domain of input variables, further subdivides the domain of discourse, and uses domain controllers on the basis of not adding fuzzy control rules [17,18], which not only simplifies the selection of the initial domain of discourse, but also improve the performance of fuzzy control.

Aiming at the problem of uncontrollable superheat of the once-through steam generator, this paper proposes an operation scheme that uses the main feed water valve to control the steam superheat and the main steam valve to control the steam pressure. On this basis, designs a variable universe fuzzy controller for steam pressure and superheat to improve the control performance of the system and ensure the quality of steam entering the steam turbine. First, design the fuzzy control rules to make the system adjust the PI controller parameters according to the change of the error; secondly, use the universe adjustment factor to adjust the universe of input and output variables to further subdivide the universe. A simulation platform based on OPC communication technology is constructed to connect the digital small reactor and the Matlab/ Simulink system. The experimental results show that the operation scheme and control scheme proposed in this paper have better system performance.

2. Operation scheme of once-through steam generator

During the operation of the once-through steam generator, considering that the outlet steam pressure and superheated steam temperature of the second loop of the once-through steam generator have certain influences on the second loop equipment and thermal cycle, this paper designs a controllable operation scheme for the steam pressure and superheat of the small reactor once-through steam generator.

2.1. Steam pressure operation method

The steam pressure control loop adopts single-loop control, which mainly controls the opening of the main steam valve and then controls the steam flow at the secondary side of the once-through steam generator. In order to enable the main steam to better track the load changes, the target load is taken as the feed-forward value is designed into the control system, and its principle is shown in Fig. 2.

When the load changes, its output adjustment signal:

$$G = G_{ref} + k_1 \Delta P + \frac{1}{\tau_1}\int \Delta P ds \quad (1)$$

where k_1 is constant of proportionality, τ_1 is integration time

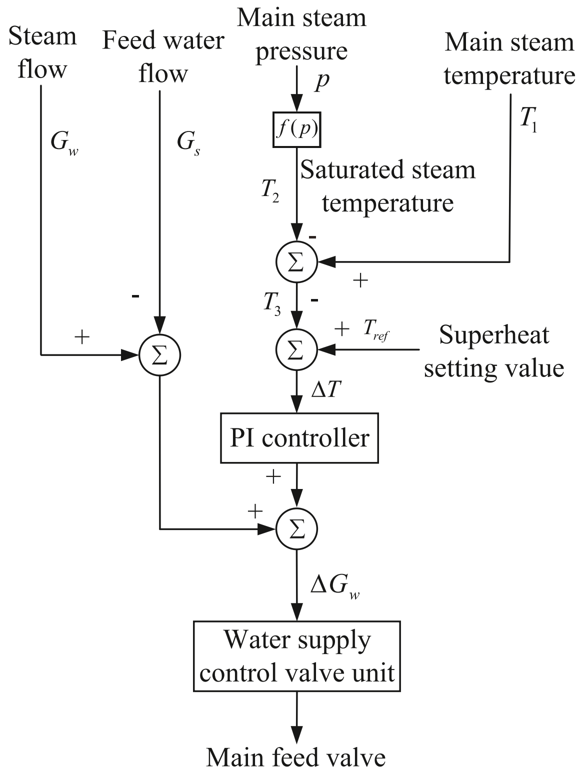

Fig. 3. Schematic diagram of steam superheat control of once-through steam generator.

constant, ΔP is outlet pressure deviation of once-through steam generator:

$$\Delta P = P - P_{ref} \tag{2}$$

and G_{ref} is the initial value adjusted by the PI controller, representing thr steam flow value, it can be read directly or calculated by formula (3):

$$G_{ref} = F(h) = h*\frac{3.0769}{h' - 0.599} \tag{3}$$

where h and h' represents specific enthalpy, which is determined by steam temperature and pressure of the system.

The main steam valve regulating unit function is:

$$y = \begin{cases} 0.005757x & (0 \le x \le 33.7) \\ 0.00597x - 0.00951 & (33.7 < x \le 66.54) \\ 0.005922x - 0.0061 & (66.54 < x \le 99.3) \\ 0.005752x + 0.01081 & (99.3 < x \le 133.0) \\ 0.005686x + 0.01959 & (133.0 < x \le 167.15) \end{cases} \tag{4}$$

where x represents steam flow, y represent opening value of main steam valve. It is worth noting that this formula matches the research object of this paper, it represents the non-linear characteristics of valve flow, in this paper, it is obtained through the bottom layer model of the platform. Its main function is to match the output result of the controller with the valve opening value, for different models, the function structure is consistent, but the parameter values will change accordingly. The same is true for formula (9).

2.2. Steam superheat operation method

The steam superheat control loop adopts cascade control. The steam temperature, steam flow and feed water flow are used as input. It mainly controls the feed water regulating valve and then controls the steam superheat at the secondary side of the once-through steam generator. At the same time, in order to eliminate the influence of steam flow disturbances, the steam flow at the outlet of the main steam valve is used as the feedforward amount of the steam superheat control system, so that it can quickly overcome the influence of load changes on the steam superheat, and its principle is shown in Fig. 3.

When the load changes, its output adjustment signal:

$$\Delta G_w = G_w - G_s + k_2 \Delta T + \frac{1}{\tau_2} \Delta T ds \tag{5}$$

where k_2 is constant of proportionality, τ_2 is integration time constant, G_w is the feed water flow; G_s is steam flow; ΔT is steam superheat deviation of the secondary side outlet of the once-through steam generator:

$$\Delta T = T_{ref} - T_3 \tag{6}$$

where T_3 is steam superheat:

$$T_3 = T_1 - T_2 \tag{7}$$

where T_1 is the steam temperature; T_2 is the saturation temperature corresponding to the steam pressure:

$$T_2 = F(P) = -1.159*P^2 + 24.04*P + 172.7 \tag{8}$$

The main feed valve adjustment unit function is:

$$y = \begin{cases} 0.4x + 40 & (-100 \le x < -50) \\ 0.667x + 53.333 & (-50 \le x < -20) \\ 0.5x + 50 & (-20 \le x < 20) \\ 0.667x + 46.667 & (20 \le x < 50) \\ 0.4x + 60 & (50 \le x \le 100) \end{cases} \tag{9}$$

3. Variable universe control algorithm

3.1. Variable universe control algorithm with improved expansion factor

In order to reflect that fuzzy control has a better control effect under the domain subdivision, this article adopts the variable universe control method. When the system error changes greatly, the control system can quickly track the target change value by increasing the value of the proportional controller; when the error change range is small, the input and output domains are adjusted by the expansion factor to make it smaller with the error further refinement, so as to achieve higher control accuracy. The control system structure diagram is shown in Fig. 4.

Given a fuzzy controller, its input and output domains are $X = [-E, E]$ and $Y = [-U, U]$ respectively, here E and U and are both positive real numbers, and relative to the variable universe, X and Y is the initial universe.

Let the universe expansion factor function $\alpha : X \to [0, 1], |x| \to \alpha(x)$ be a expansion factor of universe X, then the

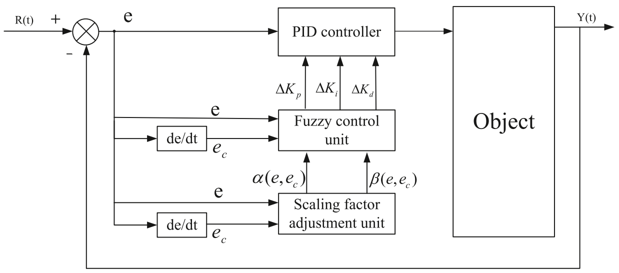

Fig. 4. Schematic diagram of variable universe control system.

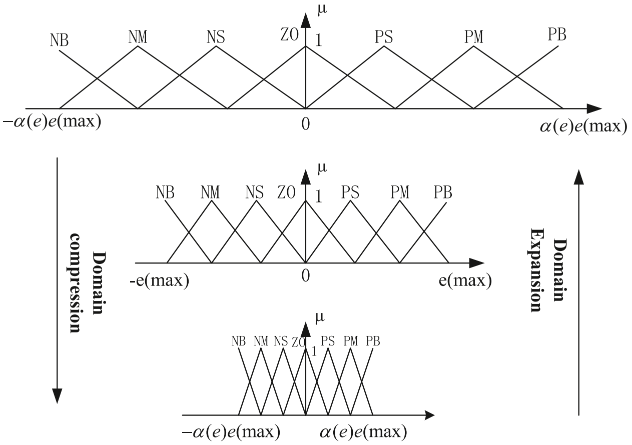

Fig. 5. Schematic diagram of domain change.

following conditions are established [19,20]:

(1) duality:$(\forall x \in X)(\alpha(x) = \alpha(-x))$;
(2) zero preservation:$\alpha(0) = 0$;
(3) monotonicity: α strictly monotonically increasing on $[0, E]$;
(4) coordination:$(\forall x \in X)(|x| \le \alpha(x)E)$;
The intuitive meaning of the expansion factor is shown in Fig. 5. It can be concluded that the universe of discourse should also meet conditions 5.
(5) regularity:$\alpha(\pm E) = 1$, $\beta(\pm U) = 1$.

This paper adopts a scaling factor designed based on a functional form, and the functional form of the designed input and output variables to improve the scaling factor is:

$$\begin{cases} \alpha(x) = 1 - \lambda \exp\left(- k_1|x| + k_2 x^2 \right), k_1, k_2 > 0, \lambda \in (0,1) \\ \beta(x) = K \sum_{i=1}^{n} p_i \int_0^t e_i(\tau) d\tau + \beta(0) \end{cases} \tag{10}$$

where K is proportional constant; e is input deviation; p_i is The i-th element in the constant vector; e_i is The i-th element in the input deviation vector.

According to the selection principle of the input and output domain adjustment coefficients and the operating characteristics of the once-through steam generator, the input and output domain adjustment factors are obtained through multiple debugging:

$$\begin{cases} \alpha(e) = 1 - 0.35\exp(-0.5|e| + 0.5e^2) \\ \alpha(e_c) = 1 - 0.7\exp(-0.9|e_c| + 0.1{e_c}^2) \\ \beta_P = (0.5|e|)^{0.1} + 0.001 \\ \beta_I = (0.35|e|)^{0.3} + 0.001 \end{cases} \tag{11}$$

where $\alpha(e)$ and $\alpha(e_c)$ are the input expansion factors of the deviation e and the deviation change rate e_c respectively; β_P and β_I are input and output scaling factor of Δk_p and Δk_i.

3.2. Design of fuzzy adaptive PI controller

According to the above analysis, the pressure and steam superheat of the once-through steam generator adopt fuzzy PI control. Fuzzy PI control is to find out the fuzzy relationship between the controller parameters k_p, k_i and the system deviation e and the rate of change e_c on the basis of the traditional PI control. After fuzzy inference, the correction values Δk_p and Δk_i are obtained. The initial values of the parameters are superimposed to achieve the effect of online correction of PI parameters. The PI parameter value at this moment obtained by fuzzy inference is:

$$\begin{cases} k_p = k_{p0} + \Delta k_p \\ k_i = k_{i0} + \Delta k_i \end{cases} \tag{12}$$

where k_{p0} and k_{i0} are initial PI parameters, Δk_p and Δk_i are based on fuzzy inference.

The structure of the fuzzy controller is double input and double output, the input variable is the system deviation e and its rate of change e_c, and the output variable is the PI adjustment value obtained by fuzzy inference. In this paper, the fuzzy domains of the steam pressure and superheat deviation e of the once-through steam generator and the rate of change e_c are all $[-6, 6]$, the fuzzy domains of the output variables are $\Delta k_p = [-1, 1]$, $\Delta k_i = [-0.1, 0.1]$, and the input and output variables are divided into 5 The fuzzy subsets are {NB, NS, ZO, PS, PB}, which represent {large negative, Small negative, Zero, Positive small, Positive large}. According to the operating characteristics of the once-through steam generator and the principle of PI parameter adjustment, the principle of obtaining the parameters of the fuzzy inference controller is:

(1) When the error e is large, in order to enable the system to have a faster response speed and track the set value, at this time, the value of k_p should be increased and the size of k_i should be reduced;
(2) When the error tend to the steady state value, in order to ensure that the system has a faster response speed and a small overshoot, the value of k_p should be gradually reduced and k_i should be gradually increased;
(3) When the error is gradually approaching the steady state value, e is smaller at this time. in order to make the system have better steady state characteristics, at this time, the value of k_p should be reduced and the value of k_i should be increased.

According to the above adjustment principles, the fuzzy rule table of the once-through steam generator control system is established as shown in Table 1:

Base on Table 1, the values of Δk_p and Δk_i are calculated using Mamdani fuzzy inference and Centroid defuzzification.

Table 1
Δk_p and Δk_i fuzzy rule table.

$\Delta k_p/\Delta k_i$		e				
		NB	NS	ZO	PS	PB
e_c	NB	PB/ZO	PS/NS	ZO/NB	NS/PS	NB/ZO
	NS	PB/ZO	PS/NS	ZO/NS	NSPS	NB/ZO
	ZO	PB/ZO	PS/ZO	ZO/ZO	NS/PS	NB/ZO
	PS	PB/ZO	PS/PS	ZO/PS	NS/NS	NB/ZO
	PB	PB/ZO	PS/PS	ZP/PB	NS/NS	NB/ZO

Table 2
Basic physical parameters of the system under 100% working conditions.

Serial number	Parameter name	Unit	Design value	Allowable error range
1	Reactor nuclear power	%	100	±1.2
2	Electric power	*Mwe*	125	±1.5
3	Secondary circuit load	%	100	±1.2
4	Feed water flow	*T/H*	596.4	±8
5	Steam flow	*T/H*	596.4	±8
6	Steam pressure	*Mpa*	4.538	±0.07
7	Stacked rod position	*step*	595	±2
8	Main feed water regulating valve	%	53.6	±1
9	Steam temperature	°C	286.6	±3

4. Simulation

The experimental verification platform is mainly composed of digital small reactor simulation platform, controller and control strategy based on Matlab/Simulink platform and OPC communication which plays a role in data transmission, in this research, the data read through the small reactor platform are steam pressure, steam temperature and feed water flow, and the data written into the small reactor platform are the opening value of the steam valve and the opening value of the feedwater valve. The digital small reactor simulation platform includes neutron dynamics and fuel dynamics model, stabilizer dynamics model, primary loop drift network model and once-through steam generator dynamics model, all models are integrated and run in different working conditions [21,22].

The simulation structure diagram of this experiment is shown in Fig. 6. The main contents of this experiment verification are:

1. Compare the control scheme mentioned in this article with the control scheme in the digital small reactor platform. The system follows during the load rise and fall. Performance and anti-interference performance;
2. Compare the variable universe fuzzy controller designed in this paper with traditional PI control and fuzzy PI control to see whether the controller designed in this paper is superior to traditional PI control and fuzzy PI in control performance control.
3. Whether the operation scheme and the variable universe fuzzy controller designed in this paper have anti-disturbance ability when the system is disturbed.

The selection of the initial value of the controller in this paper is: the initial value of the PI parameter of the superheat controller: $k_{p10} = 2.5$, $k_{i10} = 0.1$; the initial value of the PI parameter of the steam pressure controller: $k_{p20} = 30$, $k_{i20} = 0.6$, this is also the initial value of fuzzy control and variable universe fuzzy control. The Table 2 shows some design parameters of this small modular reactor platform.

4.1. Superheat follow experiment

The initial operating state of the system is stable operation under 100% working conditions, and the superheat step signal is set at 1700 s and 3400 s, with amplitudes of +5 °C and −5 °C respectively, to verify the tracking control performance of the designed controller, the superheat tracking curve, tracking error curve, and corresponding steam pressure change curve obtained from the experiment are shown in Figs. 7–9.

It can be seen from the figure that the variable universe fuzzy controller designed in this paper has better control performance than traditional PI control and fuzzy PI control. In terms of the effect of superheat step tracking control, the variable universe fuzzy controller has shorter adjustment time and less overshoot. Under the operation scheme, the outlet steam pressure of the secondary side of the once-through steam generator has better stable performance under the control of the variable universe fuzzy controller, detailed control performance indicators are shown in Tables 3 and 4, take descending period indicator as an example.

According to the Fig. 10, the system feedwater flow under PI control has a certain deviation compared with the initial state, which may be related to the steam pressure not reaching the set value, and compared with the variable universe fuzzy control, the fuzzy PI control takes longer to enter the steady state.

4.2. System load decrease experiment

The initial operating state of the experimental system is stable operation under 100% working conditions. The operating power of the system is changed by the reactor control rod switching signal at 1000 s. The specific operation method is to turn on the control rod plug signal at 1000 s and set the plug rod speed is 5 step/min, which reduces the system load, and the control rod insertion operation ends at 3000 s. This experiment is to verify the control performance of the designed controller when the load reduction, and compare the original system's status parameters changes in the load reduction process. Figs. 11–13 shows the change curve of system parameters.

It can be seen from the Figs. 11, 12 and 13 that during the process

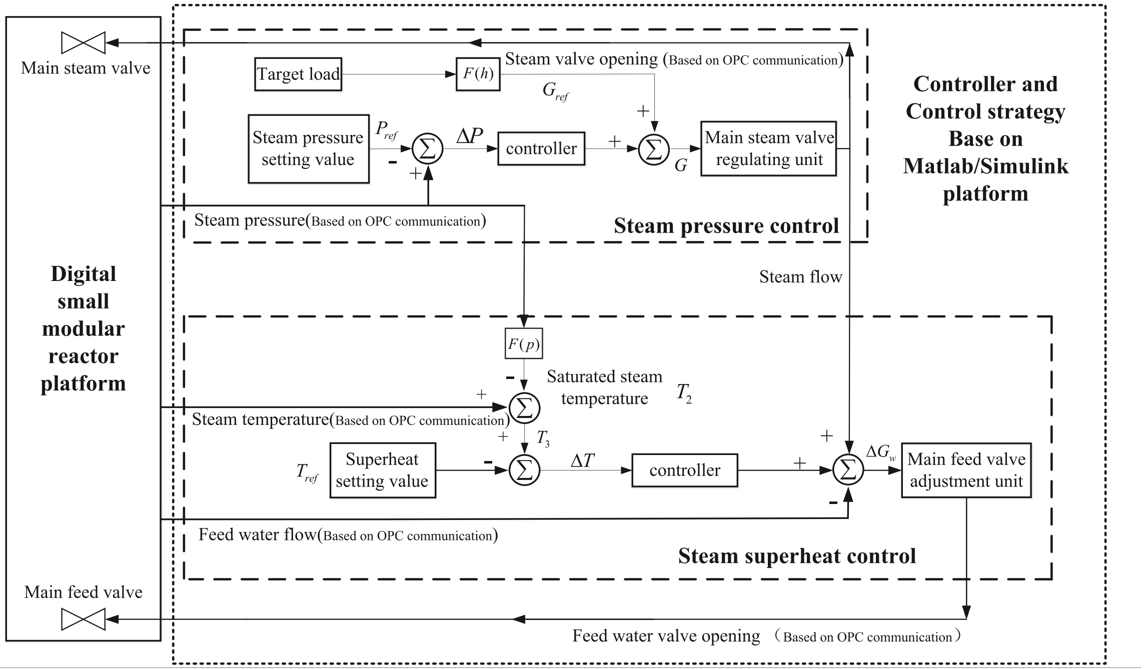

Fig. 6. Control system structure diagram.

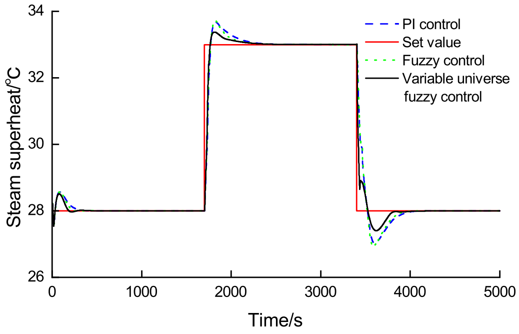

Fig. 7. Superheat follows the curve.

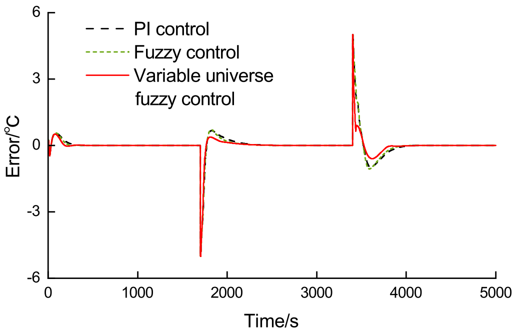

Fig. 8. Error curve.

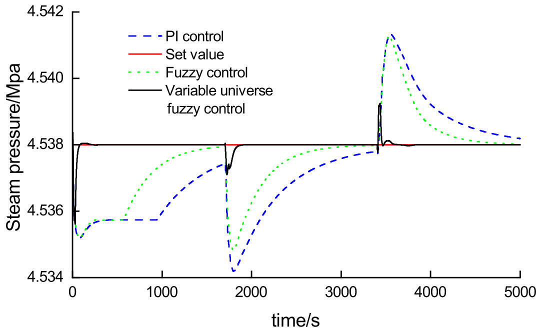

Fig. 9. Steam pressure change curve.

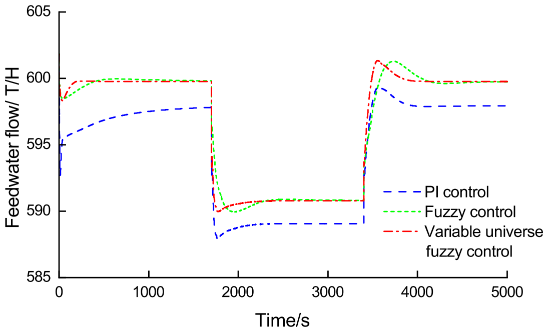

Fig. 10. The feedwater flow curve under superheat follows experiment.

of system load reduction, the original control system didn't consider the influence of steam superheat, which led a big change in steam superheat. In an operation scheme with controllable superheat has much smaller fluctuations. Moreover, compared with traditional PI control and fuzzy PI control, the designed variable universe fuzzy controller in this paper also shows better

Table 3
Superheat control performance index.

controller	overshoot/%	adjustment time/*s*
PI control	19.4	514
fuzzy control	21.2	461
variable universe fuzzy control	12	377

Table 4
Steam pressure control performance index.

controller	disturbance/*Mpa*	adjustment time/*s*
PI control	0.0045	>1700
Fuzzy control	0.0033	1303
variable universe fuzzy control	0.0012	170

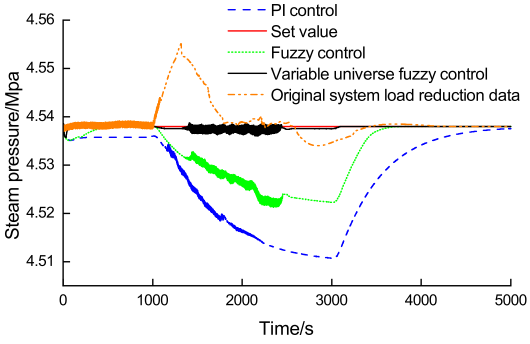

Fig. 11. Steam pressure change curve under reduced load conditions.

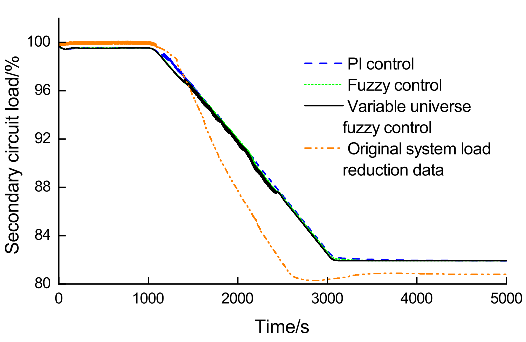

Fig. 13. Load curve.

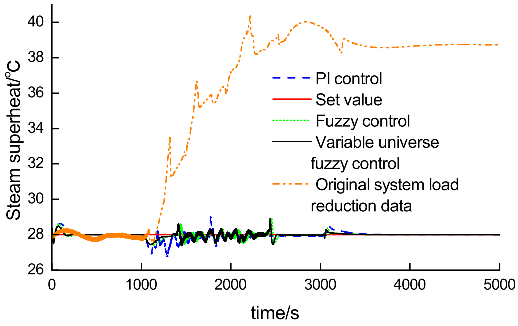

Fig. 12. Variation curve of steam superheat under reduced load condition.

control performance, its steam pressure has smaller fluctuations, and the fluctuation of system superheat due to load changes is also smaller. For specific control performance can see in Table 5.

4.3. System load increase experiment

The initial operating state of the experimental system is stable operation under 80% operating conditions. The operating power of the system is changed through the switching signal of the reactor control rod at 1000 s, so that the system load is increased to 100% operating conditions. This experiment compares the original system in system state parameters changes during the load increase process. Figs. 14–16 shows the change curve of steam pressure of the once-through steam generator, the change curve of superheat and the change curve of system load.

It can be seen from the Figs. 14, 15 and 16 that during the process of system load increase, the control effect of the control scheme is better than the control effect of the original system when the load is increased. The original system that does not consider the steam superheat control, lead to fluctuation of steam superheat and steam pressure is large. In the control scheme, the variable universe fuzzy controller designed in this paper also has better control performance, the specific control indicators are shown in Table 6.

It is worth noting that in Fig. 16 at the beginning of the experiment, the system load increased rapidly for a short period of time, and then stabilized. As shown in Fig. 15, because there is no steam superheat control strategy added to the original system, when the system enters 80% working condition, there is a large error between the steam superheat measured value and set value, the control system functions to make the steam superheat reach the set value, combining formula (5) and (7), it can be obtained that the steam temperature decreases, the reason for the decrease in steam temperature is the increase in feed water flow at this time, and the corresponding steam flow increases. The steam flow at the outlet of the secondary circuit increases, resulting in a short-term increase in the system load until the steam superheat reaches the set value.

4.4. System anti-disturbance experiment

The initial operating state of the experimental system is stable operation under 100% working conditions, and the main steam valve of the system is given a 5% step-down signal at 2000 s to verify the anti-interference performance of the system in the presence of internal disturbances, as shown in Figs. 17–18, it is the comparison curve of the steam pressure and steam superheat degree of the secondary side outlet of the once-through steam

Table 5
System load decrease experiment control index-maximum offset.

controller	steam pressure/*Mpa*	steam superheat/°C
PI control	0.0273	1.2268
fuzzy control	0.0163	0.8896
variable universe fuzzy control	0.0018	0.8894
Original system data	0.0170	12.3618

Table 6
System load increase experiment control index-maximum offset.

controller	steam pressure/*Mpa*	steam superheat/°C
PI control	0.0743	2.1174
fuzzy control	0.0235	2.4812
variable universe fuzzy control	0.0009	1.8598
Original system data	0.0789	7.3878

Table 7
System anti-disturbance experiment control index-adjustment time.

controller	steam pressure	steam superheat
PI control	2727 *s*	470 *s*
fuzzy control	1642 *s*	381 *s*
variable universe fuzzy control	117 *s*	210 *s*

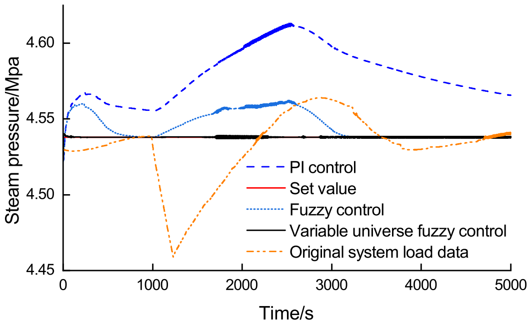

Fig. 14. Steam pressure change curve under load conditions.

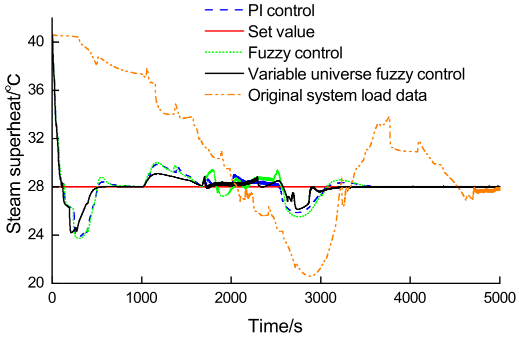

Fig. 15. Variation curve of steam superheat under load condition.

generator under different controllers.

It can be seen from the Figs. 17 and 18 that when the opening of the main steam valve suddenly decreases, the outlet pressure of the secondary side of the once-through steam generator increased instantaneously, but through simulation can be seen from the experiment that the variable universe fuzzy control has a shorter adjustment time than the traditional PI control and fuzzy PI control, which enables the system to recover to a stable state more quickly, and its superheat also has better performance, the specific control indicators are shown in Table 7.

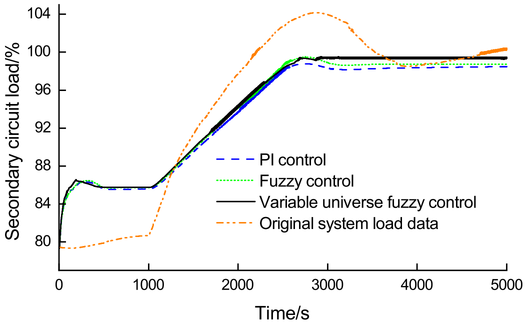

Fig. 16. Load curve.

5. Conclusion

Based on the operation scheme mentioned in this paper of the digital small reactor once-through steam generator, the digital small reactor platform and the matlab/Simulink control system simulation platform are combined through OPC communication technology to establish a control system for the steam pressure and superheat of the once-through steam generator. On this basis, a variable universe fuzzy controller for steam pressure and superheat is designed, and the following conclusions can be drawn through simulation verification:

1) Compared with the original system that does not consider the influence of steam superheat on the load increase and decrease of the system, the bistable operation scheme of steam pressure and superheat of the once-through steam generator designed in this paper has better stability in the process of system load changes.
2) Compared with the traditional PI controller and fuzzy PI controller, the variable domain fuzzy controller designed in this paper has better control performance. It not only has smaller fluctuations in the process of load increase and decrease, but also can produce less disturbances in the system and return to a stable state faster.

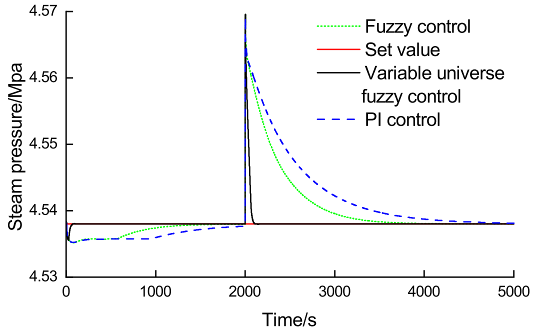

Fig. 17. Steam pressure change curve.

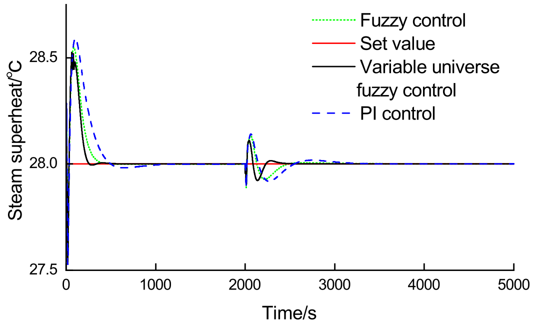

Fig. 18. Steam superheat change curve.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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