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Turbine speed control system based on a fuzzy-PID

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Abstract: The flexibility demand of marine nuclear power plant is very high, the multiple parameters of the marine nuclear power plant with the once-through steam generator are strongly coupled, and the normal PID control of the turbine speed can't meet the control demand. This paper introduces a turbine speed Fuzzy-PID controller to coordinately control the steam pressure and thus realize the demand for quick tracking and steady state control over the turbine speed by using the Fuzzy control's quick dynamic response and PID control's steady state performance. The simulation shows the improvement of the response time and steady state performance of the control system.

Keywords: turbine speed control system; fuzzy control; PID control
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1 Introduction

The once-through steam generator produces over-hot steam, having the advantages of small volume, good flexibility performance, and high heat efficiency, so the marine nuclear power plant which uses the once-through steam generator has already been extensively researched and applied abroad[1-2]. This type of marine nuclear power plant is mainly composed of the following parts[3]:

1) Reactor power control: when the load of second loop changes, it regulates the reactor power to track the load of second loop, and controls the reactor coolant's average temperature in the confined range[4].

2) Steam pressure control: when the load of second loop changes, it maintains steam pressure constant.

3) Turbine speed control: it can track the work condition of the ship to regulate the turbine to the expected speed and control the steam pressure within the fluctuated range coordinately.

The flexibility demand of marine nuclear power plant is very high, the multiple parameters of the marine nuclear power plant which uses the once-through steam generator have strong coupling relationship[5] and the major controllers need to work coordinately. The turbine speed regulated by normal PID controller can't meet the control demand, while Fuzzy control which has the advantage of strong robustness and doesn't need to have accurate mathematics model is mostly applied in the process control, except that its steady state performance is weaker than traditional PID controller. Under this condition, it is a better choice to combine Fuzzy control with PID control, taking advantage of the fast dynamic response of Fuzzy control and the steady state performance of PID control to realize the fast tracking and steady control of turbine speed. Fuzzy-PID control technique has been applied to some control systems at home and abroad recently, and achieved some success.

The turbine speed Fuzzy-PID control system is designed in this paper. The system has the coordinate control function on the steam pressure, and its control effect is verified through simulation.

2 Structure of the control system

The Fuzzy-PID controller is composed of mode converter, Fuzzy controller, PID controller and pressure deviation restrictor. The control system structure is shown in Fig.1.

The Fuzzy-PID control system has two input variables: the defined value N_0 of turbine speed and the actual speed N, steam pressure P and the actual value U_n of the main steam valve are introduced into pressure deviation restrictor. It has one output variable: the opening degree u of the turbine's main steam valve.

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In the mode converter control, when the turbine's work condition changes, under the condition that speed deviation ΔN is bigger than 20 r/min, the Fuzzy control mode is used to accelerate the system's response velocity, and better robustness is obtained. When the turbine speed deviation is reduced within the range of 20 r/min, it can be considered that the system is close to its steady state. Therefore, the PID control is used to diminish the steady error and improve control precision.

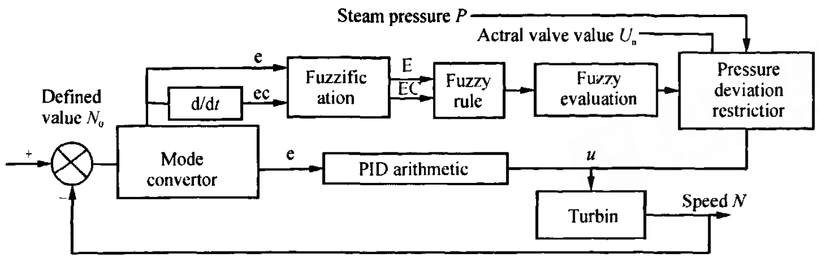

Fig.1 Schematic diagram of Fuzzy-PID control

The Fuzzy-PID control system has two input variables: the defined value N_0 of turbine speed and the actual speed N, steam pressure P and the actual value U_n of the main steam valve are introduced into pressure deviation restrictor. It has one output variable: the opening degree u of the turbine's main steam valve.
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3 The scheme of turbine speed Fuzzy-PID controller

3.1 Design of PID controller

The PID control[6] is a kind of control method which has been extensively applied. For the electricity-liquid adjusting equipments, it is better to choose incremental PID control method as the turbine speed regulating system because it has the advantage of anti-integral saturation, and it is beneficial to convert between automatic and remote controls of the speed, without initiation of the controller's output.

The general formulae of incremental PID control:

$$u(k) = u(k-1) + \Delta u(k),$$

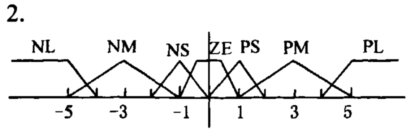
$$\Delta u(k) = K_c\{[e(k) - e(k-1)] + \frac{T_S}{T_i} e(k) + \frac{T_d}{T_S}[e(k) - 2e(k-1) + e(k-2)]\},$$

where $u(k)$ is the control output of present time, $u(k-1)$ is the control output last time, K_c is the proportional gain, T_S is the sampling period, T_i is the integral time, T_d is the differential time.

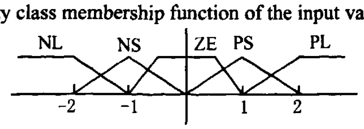
3.2 Design of fuzzy controller

3.2.1 Fuzzification process

The variety scope of accurate quantity is fuzzed up to fuzzy set theory area. The speed deviation E is divided into seven different classes of "negative large", "negative medium", "negative small", "zero", "positive small", "positive medium", "positive large", and the speed deviation ratio EC is divided into five different classes of "negative large", "negative small", "zero", "positive small", "positive large". These classes represent fuzzy subsets in fuzzy set theory area, but the size of fuzzy subset is related to the membership function[7]. The membership function is represented by triangle, trapezoid structure as shown in Fig. 2.



(a) Fuzzy class membership function of the input variable E



(b) Fuzzy class membership function of the input variable EC

Fig.2 Membership function

The output variable u has relations with seven fuzzy sets, which are simplified in the controller design: the fuzzy membership function is set with value 1 at one point, the others are set with 0, so each fuzzy set is simplified with a fixed value directly.

3.2.2 Fuzzy rule

The expression of fuzzy rule is realized by adopting fuzzy associative matrix, the number of input variables decides matrix's dimension. The principle of design for fuzzy rule: when the speed error is bigger, the output control may diminish the error as soon as possible; when the speed error is smaller, the output is smoother. It is useful for the stability of control's mode conversion. The established fuzzy control rules are shown in Table 1.

Table 1 The fuzzy control rule

ES/E	NL	NM	NS	ZE	PS	PM	PL
PL	NL	NL	NL	NM	NM	NS	ZE
NS	NL	NL	NM	NS	NS	ZE	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	ZE	PS	PS	PM	PL	PL
PL	ZE	PS	PM	PM	PL	PL	PL

In the process of actual program arithmetic, each rule presents the site information in the two-dimensional matrix, thus we don't need to store the total matrix, but to store the matrix used actually. For example, the site (1, 1) in the matrix represents the fuzzy rule:

If E=NL and EC=PL, then output U=NL

The significance of it is when the speed error is negative large and the speed error ratio is positive large, it means speed exceeds the defined value and continues to rise. The main steam valve should be closed at a faster speed so as to diminish steam flux at this time.

Give a weighted value w_{ij} to each item in the fuzzy associative matrix by minimizing the membership function:

$$w_{ij} = \min(F_{\mathrm{NL}}(\mathrm{E}), F_{\mathrm{PL}}(\mathrm{EC})),$$

where $F_{\mathrm{NL}}(\mathrm{E})$ and $F_{\mathrm{PL}}(\mathrm{EC})$ are the relevant membership functions.

3.2.3 The fuzzy evaluation output

Because the output control variables are simplified, the fuzzy set membership function is set with value 1 at one point, the others are set with 0, and then each fuzzy set is simplified and set with a given value directly. In this system, it can be simplified as follows by using the weighted average judgment method:

$$u = \sum_{ij} w_{ij} F_{ij}(U) / \sum_{ij} w_{ij}.$$

3.3 Design of mode converter

The mode converter decides whether the PID control or Fuzzy control should be adopted according to the turbine speed error ΔN. In order to avoid control fluctuation made by changing the control mode at the site of converting error, the method of setting delay error zone is adopted. Namely in the mode of fuzzy control, when ΔN is diminished to be or smaller than 20 r/min, the control mode will be converted to incremental PID control; while in the mode of PID control, the control mode will not be converted from incremental PID control to fuzzy control until ΔN is increased to be larger than 25 r/min.

3.4 Design of pressure deviation restrictor

The pressure deviation restrictor is designed in the Fuzzy-PID control. The inputs of pressure deviation restrictor are the main steam valve value U_n, steam pressure and fuzzy controller output.

The working principle of pressure deviation restrictor is like a proportional part that has a dead zone. When the pressure deviation ΔP is smaller than the dead zone, the pressure deviation will not influence turbine speed's regulation. When the pressure deviation ΔP is larger than the dead zone, the pressure deviation will limit the change speed of the main steam valve's opening degree. The larger the pressure deviation, the stronger the limit effect. When the steam pressure deviation exceeds the defined value, the main steam valve will not act lest damaging the system due to higher or lower steam pressure.

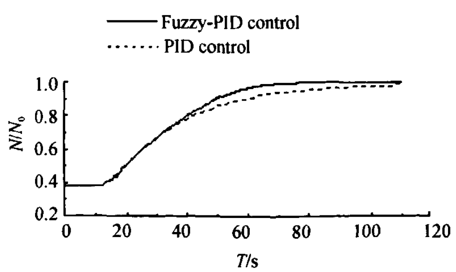
4 The simulation and result of turbine speed control

The closed loop control simulation experiment which raises and descends load quickly was performed on the simulation system of marine nuclear power plant, which has the main equipment of reactor, once-through steam generator and turbine. The performance of turbine speed Fuzzy-PID control system was researched by contrast.

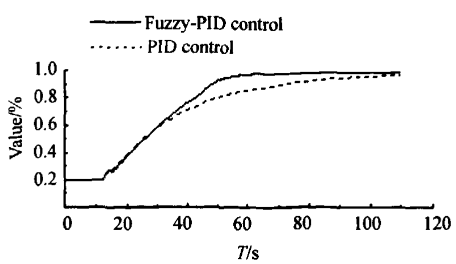
Holding the reactor power control and the steam pressure control system constant, the performances of turbine's PID control and Fuzzy-PID control were contrasted.

4.1 Load-rise simulation

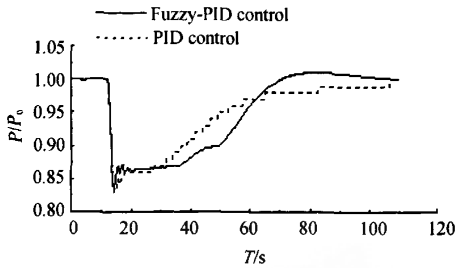
This test simulated the control process of turbine speed rapidly rising up to the rated speed from that corresponding to 20% load[8]. The turbine speed and steam pressure are unitarily processed in the figure. In Fig.3(a), when the turbine speed changes from initial value to that corresponding to 90% of the rated speed in the mode of Fuzzy-PID control, the rise time t_r =52.5 s, the peak time t_p =74 s; while in the mode of PID control, the rise time t_r = 67.0 s, the peak time t_p =94 s. In Fig.3(b), the beginning phase is consistent in the dynamic opening process of the main steam valve. In the medium phase, the Fuzzy-PID control still maintains faster opening velocity, then it is converted to PID control to process fine adjustment in the end. In Fig.3(c), the effects on steam pressure between the two control methods are compared, it shows that Fuzzy-PID control resumes the steam pressure faster.



(a) Speed dynamic response curves



(b) Dynamic response curves of the main steam valve's opening degree



(c) Steam pressure dynamic curves

Fig.3 Dynamic process of load-rise

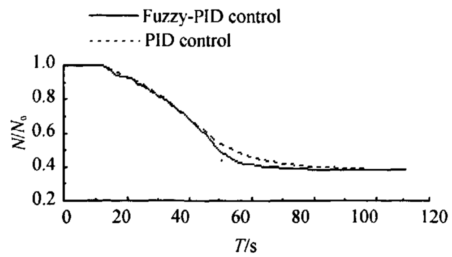
The result analysis: in order to maintain steam pressure within the defined range in the dynamic process, proper control parameters should be chosen in the PID control lest the main steam valve opens too fast and the once-through steam generator's product can't meet the demand of turbine's rising speed, which will cause too low steam pressures. Thus the PID control's response speed is slower, while in the Fuzzy-PID control, the fuzzy control is adopted in the phase of changing work condition, which will accelerate the response speed, and in the meantime, the designed steam pressure deviation restrictor ensures the steam pressure in a defined range. When the speed error ΔN is smaller than 20 r/min, the control will be converted to PID mode so as to diminish the speed error and improve the control precision step by step.

4.2 Load-descend simulation

This test simulated the control process of turbine speed rapidly descending to low speed corresponding to 20% load from the rated speed. In Fig.4(a), the steam turbine speed changes from initial value to that of 90% of the rated speed in the Fuzzy-PID control, the rise time t_r =50.0 s, the peak time t_p =70.5 s. While in PID control, the rise time t_r =59.0 s, the peak time t_p =89 s. In Fig.4(c), the effects on steam pressure between the two control methods are compared, Fuzzy-PID control resumes the steam pressure faster, however it has small magnitude fluctuation.

The result analysis: the main steam valve should not close too fast in the process of descending load lest steam accumulation owing to thermal inertia. Therefore, the response speed of normal PID control is restricted and its regulation is slower.

The Fuzzy-PID control adopts fuzzy control to accelerate the response speed in the beginning phase of changing speed, and the designed steam pressure deviation restrictor ensures that the steam pressure does not exceed the fixed pressure. When the speed error $\Delta N \leqslant 20$ r/min, it is converted to PID control to diminish the speed error and improve the control precision step by step.



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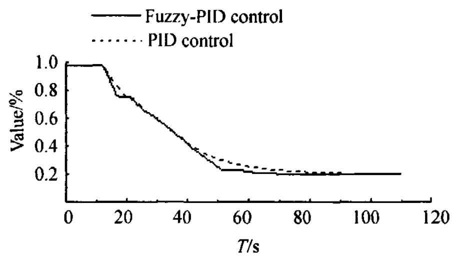
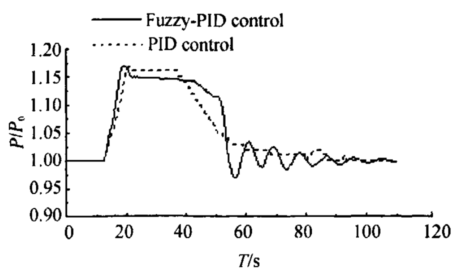


(b) Dynamic response curves of the main steam valve's opening degree



(c) Steam pressure dynamic curves

Fig.4 Transient of load-descend

5 Conclusions

The turbine speed Fuzzy-PID control system combining the coordinate control of steam pressure is designed in this paper. This control system not only has strong robustness and fast response of Fuzzy control, but also has the advantage of diminishing steady error and improving the control precision of normal PID control. The control simulation experiment shows that this control system can maintain steam pressure in the defined range coordinately and improve the system's response time and steady state precision obviously.

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