The Design for Feed Water System of Boiler Based on Fuzzy Immune Smith Control

GuiLi YUAN
School of Control and Computer Engineering, NCEPU, Beijing, China
Email: ygl@ncepu.edu.cn

JiZhen LIU
School of Control and Computer Engineering, NCEPU, Beijing, China
Email: xyg@ncepu.edu.cn

***Abstract*—Aiming at the uncertainty of model parameters and dominate time delay of the controlled object in feed water system of boiler, combined with improved Smith predictor control method and fuzzy immune PID control method, improved Smith predicting controller based on fuzzy immune is designed.**

Fuzzy Immune PID controller can self-tune parameters, and has adaptive capacity to the diversification of controlled object parameters. When there is the phenomenon of large delay, the predictor estimates in advance the dynamic characteristics of the process under basic disturbance, so that regulator takes action ahead of time to reduce the overshoot. The designed controller is applied to the feed water cascade control system, and is simulated by Matlab under different operating conditions. Simulation results show that the designed control system has strong adaptive ability to the diversification of model parameters. And its stability, accuracy are superior to that of conventional Smith control system. The effectiveness of this designed controller has been confirmed.

***Index Terms*—immune control, feed water system, smith control, fuzzy immune control**

I. INTRODUCTION

The maintenance of the water level of boiler drum in a certain range is a major indicator which maintains the safe operation of turbine and boiler. Too low or too high water level will affect the operation safety, economy of turbine and boiler. At present, water level control strategy has a variety of sophisticated control methods including single-impulse control method, two impulses control method and three impulses control method, and so on. However, in a specific industrial field, the high automatic input rate for water level control can not be guaranteed. So a strong robustness, relatively simple and fast algorithm is in urgent need [1]. Smith predicting compensation method is widely used in the time delay system, but too sensitive for model diversification. In this study, the improved Smith predicting compensation control strategy based on fuzzy immune will be applied to water level control of drum. This strategy gives full play to robustness and rapidity of fuzzy control and immune control, and improves the sensitivity to the model. Simulation results show that the boiler drum water level control system using this new strategy has good dynamic adjustment quality and strong robustness.

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II. IMMUNE CONTROL

A. Immune Feedback Mechanism

Immunization is a characteristic physiological response of the organism. Biological immune system can produce antibodies against invading antigens. After antibody and antigen binding, a series of reactions will occur. Antigen was destroyed by phagocytes or special enzymes effect. Immunization includes humoral immunity and cellular immunity. Immune response is completed by the interaction between different sub-groups T cell. T_H cell (helper T - cell) and T_S cell(suppressor T - cell) are important immune regulating cells. T cell plays a key role in the immune response ,which mainly draw on feedback regulation mechanism of T cell. For simplicity, we mainly consider the reaction between B cell and T cell, that is, the response between antigen (A_g), antibody (A_b), B cell, supporting T cell (T_H) and suppressor T cell (T_s). Taking humoral immune response as an example, the APC (Antigen Presenting Cell) digests antigen. First of all, it activates T_H cell, and releases lymphocyte. Then the B cell is activated to produce antibody. Antigen-presenting of APC can slowly activate T_s cell, which can inhibit T_H cell and B cell to ensure the stability of the immune system. This is the principal feedback mechanism above. The interaction between inhibition mechanism and the main feedback mechanism applies the rapid response of the immune

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feedback mechanism to the antigen, and the rapid stability of the immune system to achieve. The regulation of T cell in immune response is shown in Fig. 1 [2].

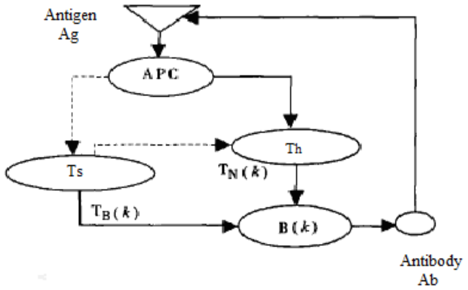


Figure. 1 Response chart of B cells in humoral immunity

B. Immune Feedback Control Algorithm[2,3,4,5]

Based on the immune feedback principle, we consider the following simple feedback mechanism. Supposing the number of the k generation antigens: $\varepsilon(k)$, the output of antigen-stimulated T_H cell: $T_H(k)$, and the Impact T_S cell to B cell is $T_s(k)$. Then the total stimulus $S(k)$ that B cell receives:

$$S(k) = T_H(k) - T_S(k) \tag{1}$$

Where:

$T_H(k) = k_1\varepsilon(k), T_s(k) = k_2 f(\Delta S(k))$

If the number of antigens $\varepsilon(k)$ is act as the deviation $e(k)$, and the total stimulus $S(k)$ that B cell receives is act as control input $u(k)$. Then the following feedback control law:

$$u(k) = K\{1 - \eta f[\Delta u(k)]\}e(k) = k_p e(k) \tag{2}$$

Where:

$K = k_1$, K : to control reaction speed

$\eta = \dfrac{k_2}{k_1}$, η : to control stabilizing effect

$f(\cdot)$:non-linear function.

Seen from Eq. (2), the controller based on immune feedback principle is actually a non-linear P controller [1,6].

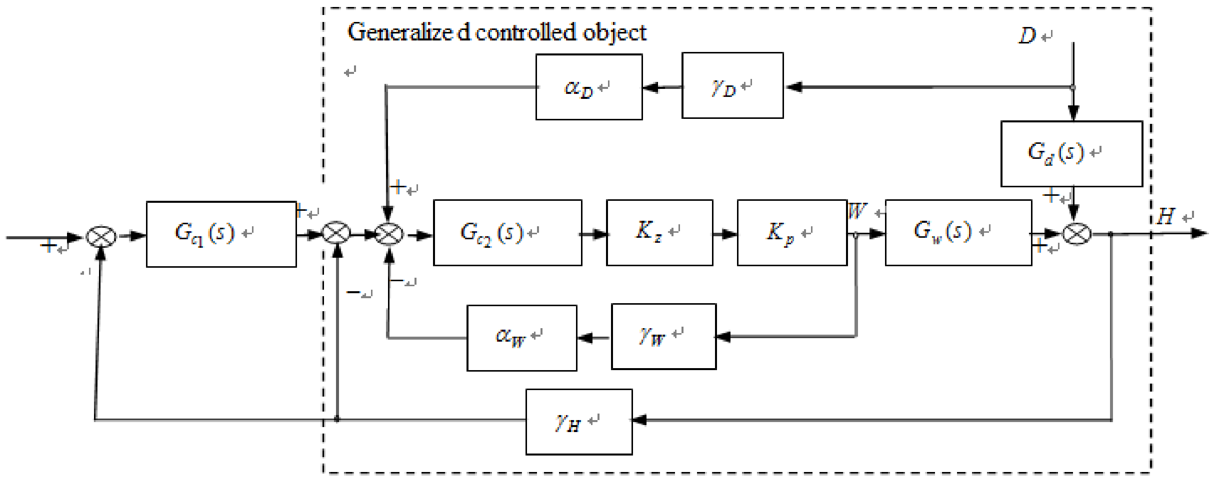


Figure. 2 The cascade three impulses control chart for drum water level

C. Improved Smith Predicting Compensation Control

If Smith Predicting control system can accurately predict model, this method can obtain good control effect, and greatly improve control quality. But the thermal control system with a large delay is difficult to establish accurate mathematical model. The Smith Predicting Controller is very sensitive to model error, so it is difficult to widely use in the thermal control. Improved Smith predictor proposed by Hang, it adds in a regulator based on the original program. The block diagram are shown in Fig. 2, Kp=1[7].

Seen From the Fig. 2, the main difference between improved Smith predictor and Smith predicting compensation strategy is transfer function of feedback channel in the main feedback loop is not 1 but $G_f(s)$.

$$G_f(s) = \frac{G_{c2}(s)g_m(s)}{1 + G_{c2}(s)g_m(s)} \tag{3}$$

$G_{c1}(s), G_{c2}(s)$ are all PI regulators to ensure output response of the system has not steady-state error. The primary regulator $G_{c1}(s)$ adjusts on the basis of the circumstances that models exactly match. Auxiliary regulator setting seems to be complex, but auxiliary regulator in the feedback channel constitutes $G_f(s)$ with model transfer function $g_m(s)$. Assuming that $g_m(s)$ is a first-order inertia link $\dfrac{1}{T_m s + 1}$, and integral time constant in $G_{c2}(s)$ is $T_{i2} = T_m$. That is, regulator integral time is equal to time constant of the model. $G_f(s)$ can be simplified as:

$$G_f(s) = \frac{1}{\frac{T_m}{K_{c2}K_m}+1} = \frac{1}{T_f s+1} \tag{4}$$

Feedback loop has a first-order filter which has only one tuning parameter T_f. Seen from Eq. (4), only the proportional gain K_{c2} in $G_{c2}(s)$ need to be set, and it is easier to adjust on line. This paper simulates by using such a control strategy in the feed water control process, in order to further understand the improved strategy impact on system performance.

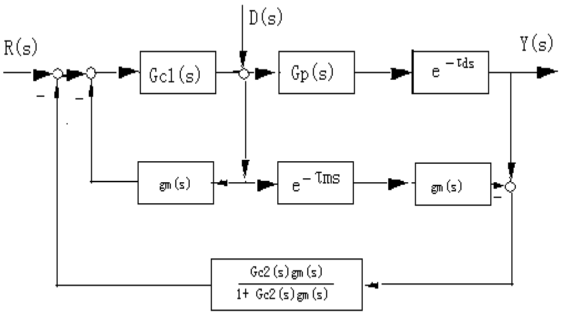


Figure. 3 The block diagram of improved Smith compensator system

III. Feed Water of Boiler Control System

Water level cascade three impulse control system are shown in Fig. 3.

In the Fig. 3:

H, H_0: water level output value and the given value

D, W: steam flow and feed water flow

$G_w(s), G_d(s)$: the transfer function of water flow to water level and the transfer function of steam flow to water level:

$$G_w(s) = \frac{\varepsilon}{s(Ts_1+1)}, G_d(s) = \frac{K_d}{T_2 s+1} - \frac{\varepsilon}{s} \tag{5}$$

$\gamma_D, \gamma_W, \gamma_H$: transfer coefficient of steam flow D, transfer coefficient of feed water flow W and the transfer coefficient of water level measurement transmitter H

α_D, α_W: sub-pressure coefficient of steam flow and sub-pressure coefficient of feed water flow K_Z, K_P: characteristic coefficient of implement agencies and the characteristic coefficient of valve [6].

Comparing to the general single-stage three impulse water level control system, two regulators complete water control task in this control system. Vice regulator $G_{c2}(s)$ task is to eliminate spontaneous disturbance of water flow caused by pressure of feed water fluctuation, and quickly adjusts feed water flow when the steam load changes, to ensure the balance between feed water flow and steam flow. The primary regulator $G_{c1}(s)$ task is to ensure the water level without the static error. Feed-forward channel is used to compensate for external disturbances to overcome the "false water level" phenomenon. Thus, when the load changes, the water level stable value depends on the primary regulator to maintain, and it does not require the steam flow signal intensity which enter to the vice regulator carry out the set according to "static ratio" [6].

The parameters of object in Fig. 3:

$$\varepsilon = 0.037, K_d = 3.6, T_1 = 30, T_2 = 15, \gamma_D = \gamma_w = 0.08,$$

$$\gamma_H = 0.033,$$

$$\alpha_D = \alpha_w = 0.21, K_z = 10, K_P = 2$$

When the controller $G_{c2}(s)$ takes $K_{c2} = 0.4648$, the approximated, generalized controlled object model and disturbance output model respectively are [1]:

$$G_{mv}(s) = \frac{3.0303}{80s+1} e^{-25s}, G_{md}(s) = \frac{-3.25}{60s+1} e^{-100s} \tag{6}$$

IV. The Design of Improved Smith Controller Based on Fuzzy Immune

Taking into account the difficulty of the selection of parameters K, η and non-linear function $f(\cdot)$, this paper applies fuzzy logic reasoning to approximate the nonlinear function $f(\cdot)$, then adjusts real-time the proportional gain K_p of PID controller based on fuzzy immune feedback mechanism. The composition form of primary controller PID is: $G_c(s) = k_p + k_i \frac{1}{s} + k_d s$.

In the dynamic process, proportional, integral and differential play different roles. The relationship between the performance in time domain and k_p, k_i, k_d is shown in Table.1.

Table I.
The Relationship between Adjusting Parameters of PID and the Performance in Time Domain

Parameter	Rise time	Overshoot	Transition time	Static error
k_p increase	decrease	increase	decrease of variation	decrease
k_i increase	decrease	increase	increase	elimination
k_d increase	decrease of variation	decrease	decrease	decrease of variation

Seen from Table.1, when PID parameters increase, the performance of system makes the changes. The relationship in Table. 1 is relative in a certain range. k_p, k_i, k_d, the change for every parameter takes different effect on system performance.

At the same time, this paper applies fuzzy controller to tune online integral coefficient k_i and derivative coefficient k_d of PID controller, to achieve adaptive control [2,7].This paper introduces the framework of the control system, which is a new control strategy combined by the controller and improved Smith predictor. The framework of the control system is presented in Fig. 4.

Using fuzzy rules to approximate the nonlinear function f (•), each input variable is fuzzed by two fuzzy sets, respectively the "positive" (P), "negative" (N). Output variable is fuzzed by three fuzzy sets, namely, the "positive" (P), "Zero" (Z) and "negative" (N).

Membership function defined on (- ∞, + ∞). According to "the greater stimulus that cell accepts, the smaller the suppression ability is" and" the smaller stimulus that cell accepts, the greater the suppression ability is ", the following four fuzzy rules are used [4].

r1: If u is NB and Δu is NB, then f (u, Δu) is PB.
r2: If u is NB and Δu is NM, then f (u, Δu) is PB.
r3: If u is NB and Δu is NS, then f (u, Δu) is PM.
r4: If u is NB and Δu is ZO, then f (u, Δu) is PM.

The membership functions of u, Δu, and f (•) are shown in Fig. 5.

In the Fig. 5:
PB: the positive big.
NB: the negative big.

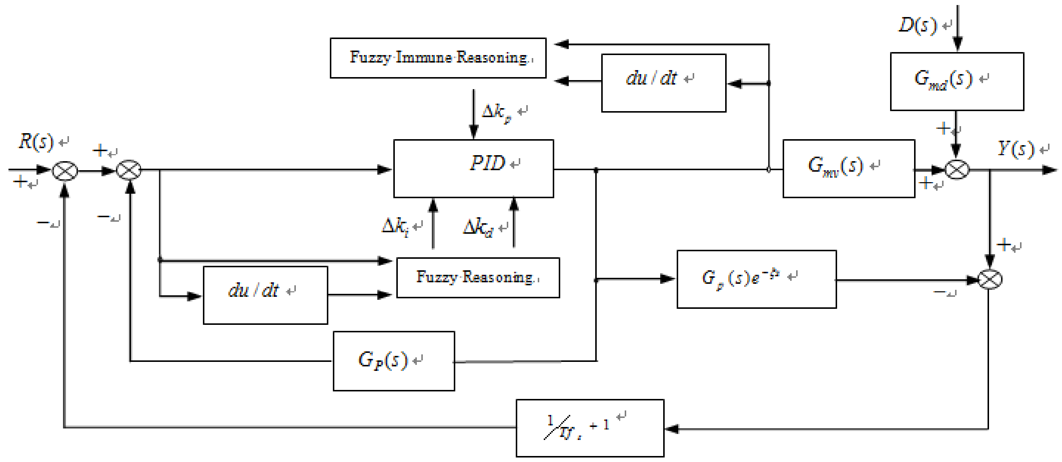


Figure. 4 The improved Smith control chart based on fuzzy immune for boiler drum water level

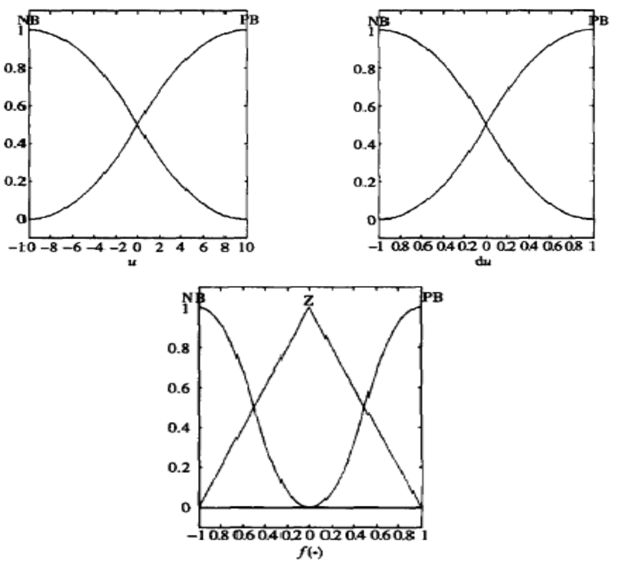


Figure. 5 The membership function for u, du, and f (.) of the fuzzy immune PID

When fuzzy control rule table for k_i, k_d has been built as shown in Table. 2 and Table. 3, according to the following method, we can do adaptive correction on k_p, k_i, k_d. The range of the system error e and the range for change rate of error ec are defined as field on fuzzy sets, that is, e,ec={-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6}. Fuzzy subset e,ec＝{NB,NM,NS,ZO,PS,PM,PB}, elements of subset respectively represent the negative large, negative, negative small, zero, positive small, positive middle, positive large. Supposing e, ec, and k_p, k_i, k_d are subject to normal distribution, then the membership of each subset can be obtained. According to membership assignment form of the fuzzy sets and the fuzzy control model, we design fuzzy matrix for PID parameters using fuzzy synthetic reasoning, and find modified parameters which are used into the following formula.

$$
\begin{aligned}
k_p &= k_p' + \{e_i, ec_i\}_p \\
k_i &= k_i' + \{e_i, ec_i\}_i \\
k_d &= k_p' + \{e_i, ec_i\}_d
\end{aligned} \tag{7}
$$

TABLE II.
FUZZY RULE OF k_i

ec \ e	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

TABLE III.
FUZZY RULE OF k_d

e \ ec	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

In the online operation process, the control system complete the online self-correction on PID parameters of the main controller, through the results processing of the fuzzy logic rules, table and computing.

According to the control scheme proposed in this paper, we take the object model of generalized feed water in Fig. 2 and the disturbance model into the control system structure diagram in Fig. 4 using Eq. (6). This paper uses the advantage that fuzzy control can approximate an arbitrary non-linear link and robustness, to apply control experience of the operator and expert to the control process, and draw on speed of immune feedback response and immune stability to improve the control quality. It makes control scheme have good rapidity, robustness and adaptive capacity.

V. SIMULATION

This paper applies Simulink tools to program, then to do analysis, calculation and simulation work easily and intuitively.

When the object model matches, fuzzy immune Smith control scheme and Smith control scheme are used to simulate respectively. Then simulation results are shown from Fig. 6 to Fig. 9. The figures respectively corresponds to two schemes when delay time constant increased by 10%, the delay time constant increased by20%, the inertia time constant increased by 10%, the inertia time constant increased by 20%. Reaching the steady state, at t = 500s, the 20%disturbance of steam flow has been added. From Fig. 6 to Fig. 9, chart (a) and chart (b) respectively represent response curves comparison using fuzzy immune Smith scheme and Smith control scheme. Curve 1 and curve 2 respectively represent the comparison between the response curve for the no-changed parameters and the response curve for the changed parameters using the corresponding control strategy. Fig. 6(a) is the response curve using fuzzy immune Smith when delay time increase by 10%. Curve 1 is the response curve for nominal parameters, but curve 2 represents the response curve when the delay time increases by 10%. So, seen from the comparisons, when the model match or mismatch, the fuzzy immune Smith control has small overshoot and the short regulating time. And, when the system occur the disturbance of the set value or the external load disturbance, Smith predictor control is very sensitive to the accuracy of the model, but fuzzy immune Smith program has excellent adaptability and robustness.

If the expert experience of fuzzy control rules can be detailed to make more effective control rules, the control effect of Smith predicting controller based on fuzzy immune will be excellent.

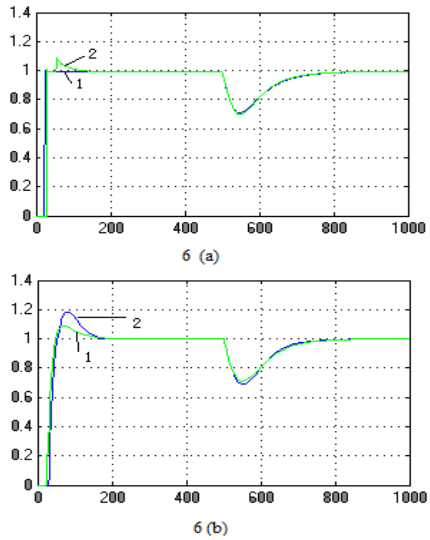


Figure. 6 Simulation result that τ increases by 10%

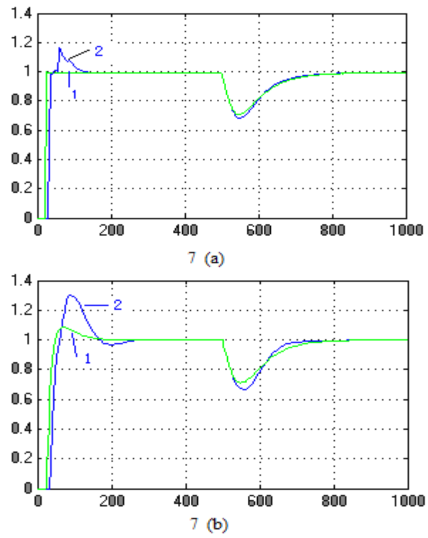
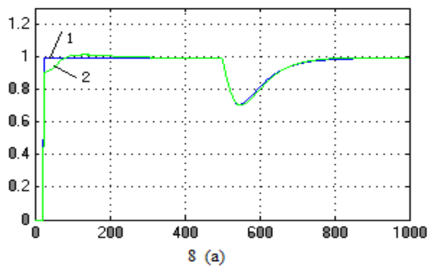


Figure. 7 Simulation result that τ increases by 20%



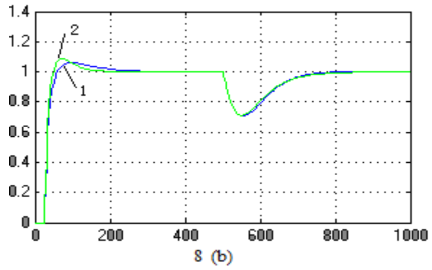


Figure. 8 Simulation result that T increases by 10%

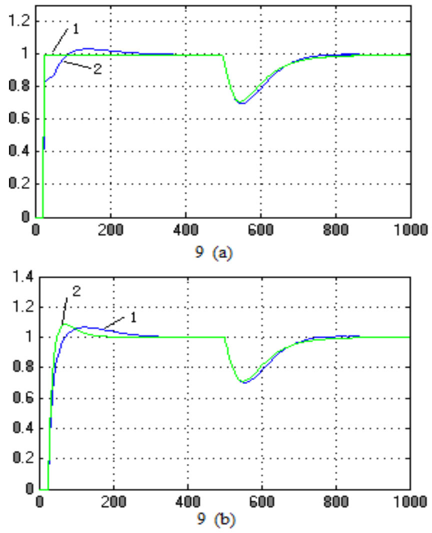


Figure. 9 Simulation result that T increases by 20%

VI. CONCLUSION

Seen from Fig. 6, Fig. 7, Fig. 8 and Fig. 9, Smith control scheme, improved Smith predicting control program and improved Smith control scheme based on fuzzy immune, regardless of the changes appear in the model match or the model parameters, the control performance is improved step by step. Especially improved Smith control scheme based on fuzzy immune presented in this paper can significantly improves adjustment time, the overshoot, and robust stability. It also effectively improve the system performance of control system for coordination feed water.

If the expert experience of fuzzy control rules can be detailed to make more effective control rules, the control effect of Smith predicting controller based on fuzzy immune will be excellent.

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GuiLi Yuan NeiMengGu Province, China. Birthdate: October, 1971. is Control Science and Engineering Ph.D., graduated from School of Control and Computer Engineering North China Electric Power University. And research interests on information control, advanced control strategy and its application in power plant control.

She is a associate professor of School of Control and Computer Engineering North China Electric Power University.

JiZhen Liu Shanxi Province, China. Birthdate: Aug, 1951. is Control Science and Engineering M.E, graduated from School of Control and Computer Engineering North China Electric Power University. And research interests on optimal control of power plant.

He is a professor, and PhD supervisor of School of Control and Computer Engineering North China Electric Power University.