2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

Application of The Fuzzy Gain Scheduling IMC-PID for The Boiler Pressure Control

Xiao-Feng Li, Shi-He Chen
Electric Power Research Institute of Guangdong Power Group Co.
Guangzhou, P.R. China
13660239839@139.com

Ruiyuan Wu
School of Electronic and Information Engineering
South China University of Technology
Guangzhou, P.R.China.

***Abstract*—In this paper, the use of a Fuzzy Gain Scheduling IMC-PID (FGS+IMC-PID) scheme has been presented based on fuzzy performance degree coefficient η self-adjusting controller for the improvement of IMC-PID control. It is shown that the IMC-PID controller with the Fuzzy PID parameters Gain Scheduler provides satisfactory closed-loop responses with less overshoot and shorter rising times in case of both set point disturbance and the plant/model mismatch. Simulations are given, in which the proposed method is compared to other PID tuning methods (IMC, SPMG). The proposed scheme is suitable to implement in the complex process control system in power generation, since it does not demand significant computing resources. It has already been implemented through Function Code in many typical DCS (EDPU, XDPS, Ovation etc). The industrial applications show that the scheme achieves better performance in specific load variation range.**

Keywords-IMC control, fuzzy self-adjusting, fuzzy gain scheduling, boiler-turbine coordinated control

I. INTRODUCTION

Nowadays, the super-critical units have become the main units in China's electric power industry. Despite the significant progress in the past decades in hardware and software, the predominant control technology is still the PID controller in the super-critical units. With the development of the power system, it is more and more difficult to deal with the nonlinearity, uncertainty and high-order inertia of the process in the units by using classical PID controllers. In this case, advanced PID design techniques become very appealing.

In recent years, a number of advanced tuning techniques for PID controllers have been presented in literature[1] [3] [6]-[8], among which the internal model control (IMC) approach has been proven to be effective in complex industrial process control.

The IMC compares the process output to the predicted output and uses the inverse model to reduce the error. If the predicted output and the measured output are equal, the error is zero and the controller operates as a feedforward controller. This technique provides good robustness for uncertain processes. It is later used to design robust PID controllers.

One limitation of the IMC is that a fixed performance degree ( ) is used. The controller is not flexible enough to guarantee a fast response and good robustness for time-variant uncertainty.

Fuzzy gain scheduling can be used to solve some complex control problems. The effectiveness of this method has already been validated by many applications [3]-[5].

In order to make the IMC-PID control-loop act faster and more robust, a fuzzy gain scheduling scheme is proposed in this paper to tune the IMC-PID control parameters online. The performance degree coefficient η is defined and η is determined by a fuzzy controller based on the error (e) and change of error (△e) of the dynamic process. Then the PID controller parameters are determined by a gain scheduling.

The industrial applications show that this control scheme improves the robustness of the control system significantly. One merit of this scheme is that it does not demand too much computing resources. It has been implemented in many typical DCS (EDPU, XDPS, Ovation etc) by using their embedded function module.

II. IMC PID DESIGN

Many complex processes in power generation, such as the boiler-turbine process., have non-linear dynamics with time-varying parameters, unknown disturbances and high order of the inertia. Until now, the control efforts have almost exclusively been made on traditional PID feedback control, but the classic PID controllers are unable to deal with changing disturbances and dynamics. In this session, we adopt the IMC for the design of the tuning PID controllers.

A. IMC-PID design

The IMC control design is briefly reviewed first. A rigorous proof can be found in [6] and [10]. Consider the unity feedback control system. G (s) denotes the plant and C(s) denotes the controller.

In this paper, the first-order with time delay process is studied:

$$G(S) = \frac{Ke^{-\theta s}}{\tau s + 1} \tag{1}$$

where K is the gain, τ is the time constant, and θ is the time delay.

The H_∞ PID can be written as [10]:

$$C(s) = \frac{(1+\theta s/2)(\tau s+1)}{Ks(\lambda^2 s + 2\lambda + \theta/2)} \tag{2}$$

Comparing the above controller with the following practical PID controller:

$$C(s) = K_c\left(1 + \frac{1}{T_I s} + \frac{T_D s}{T_F s + 1}\right) \tag{3}$$

The parameters of the PID controller are derived as follows.

$$T_F = \frac{\lambda^2}{2\lambda + \theta/2} \tag{4a}$$

$$T_I = \frac{\theta}{2} + \tau - T_F \tag{4b}$$

$$T_D = \frac{\theta\tau}{2T_I} - T_F \tag{4c}$$

$$K_C = \frac{T_I}{K(2\lambda + \theta/2)} \tag{4d}$$

where λ is called the performance degree.

B. DCS PID control algorithm

In DCSs such as EDPF-NT, OVATION, the PID algorithm is in the form of :

$$Output = \left[K_P + \frac{1}{\tau_I * S} + \frac{K_D * \tau_D * S}{\tau_D * S + 1}\right] error \tag{5}$$

where:

K_P= Proportional gain;
τ_I = integral time constant;
τ_D = derivative time constant;
K_D= Derivative lag constant。

Substitute (4a-4d) into (5), the parameters of the PID controller in terms of the adjustable parameter λ are obtained as follows:

$$K_p = K_C \tag{6a}$$

$$\tau_i = T_I / K_C \tag{6b}$$

$$\tau_d = T_F \tag{6c}$$

$$K_d = T_D \times K_C / \tau_d \tag{6d}$$

λ is directly related to the performance and robustness of the closed-loop system. Decreasing λ will improve the load disturbance rejection performance of the closed-loop but deteriorate its robustness in the presence of the actual process uncertainty. On the other hand, increasing λ tends to strengthen the closed-loop robustness but will decay its disturbance rejection performance. The relationship between λ and control performance is monotonic. Usually, the value of λ can be chosen within the range of 0.1θ-1.2θ [10].

For the purpose of calculation, the performance degree coefficient η is defined in this paper: $\eta=\lambda/\theta$.

Normally, the performance degree is a fixed value in the IMC controller, while the process parameters may change. This implies that the classical IMC is not flexible enough to guarantees good performance and robustness when the uncertainty changes with time. To solve the problems, a FGS+IMC-PID scheme is proposed in next section，where η is using tuned online fuzzy gain scheduling.

III. FUZZY-IMC- PID SCHEME

The new control scheme is shown in Fig 1, which is comprised of a fuzzy self-adjusting controller for η, PID parameters fuzzy gain-scheduler, together with a standard IMC-PID controller.

A. Fuzzy self-adjusting controller for performance degree

Fuzzy self-adjusting controllers have been widely applied in industry since their development. [3-5] They can reject stochastic disturbance and improve the performance of the control loops efficiently. The object of this section is to develop a self-adjusting controller for the IMC-PID controller.

In the design procedure of a fuzzy controller, the knowledge from step response analysis, process dynamics, and extensive simulation study is converted into fuzzy rules and relationship base. This rule base is used by a fuzzy inferential engine to obtain the value of η online according to the variance of the process parameters. The proposed fuzzy self-adjusting IMC-PID controller is shown in Fig.1. The design procedure is as follows.

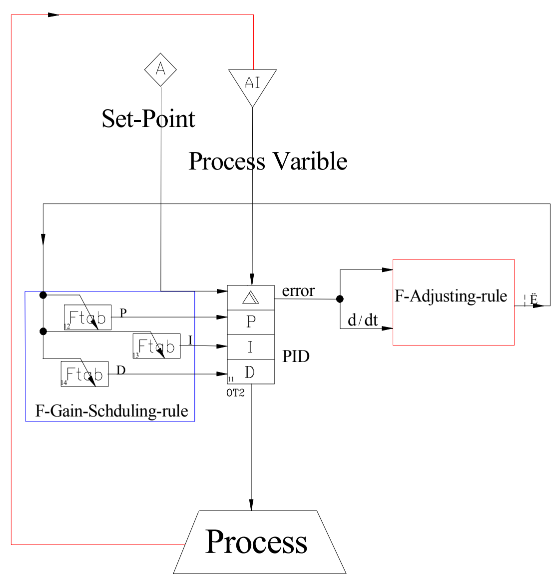

Fig. 1. Control scheme of FGS+IMC-PID controller

There are two fuzzy inputs: the error $e(k)$ and the derivative of error $\Delta e(k)$. The output is λ, which is derived from fuzzy rule base by a fuzzy self-adjusting controller.

The η for the IMC-PID parameters is determined based on a set of fuzzy rules of the form:

IF e is A_i and Δe is B_i THEN $\eta=\eta_i$. (7)

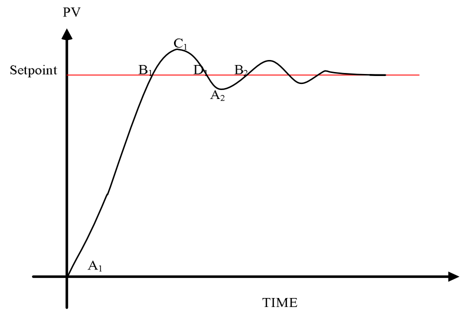

Fig. 2. Process step response

The fuzzy self-adjusting controller will generate an η(k) for the given instant values of e(k) and Δe(k) at time t. To ensure a speedy inferential, The membership functions for the error e(k) and the derivative of error Δe(k) variables are shown in figures 3 and 4 with eleven fuzzy subsets: negative very big (NVB), negative big (NB), negative medium (NM), negative small (NS), negative very small (NVS), zero (Z), positive very small (PVS), positive small (PS), positive medium (PM), positive big (PB) and positive very big (PVB).

The membership functions for input variables are defined with triangular and trapezoidal shapes (Fig.3 and Fig. 4).

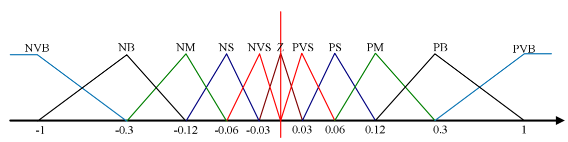

Fig.3 Membership functions for e(k)

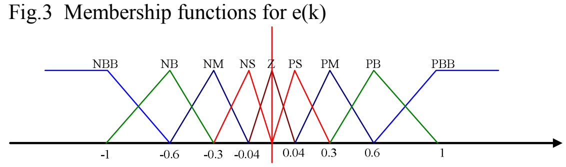

Fig.4 Membership functions for Δe(k)

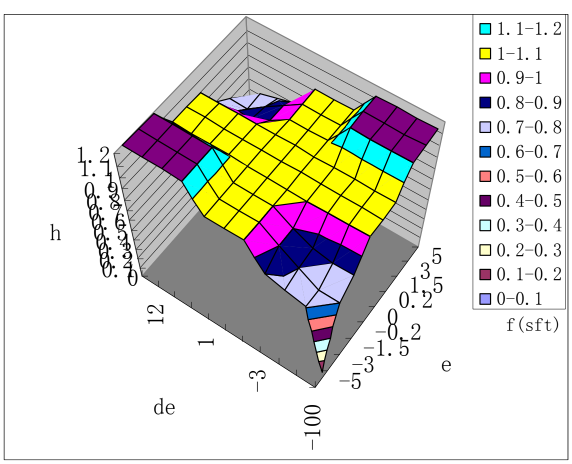

Fig.5 Output surface graph of adjusting coefficient η

The rule sets are established in the surfaces shown in Fig.5, which are used to determine η.

After determining η, the PID controller parameters can be updated with the IMC-PID formulae (Eq. 4 and 6). Then, the relationship between each parameter of the IMC-PID and the coefficient λ is plotted in Fig.6 - Fig.9.

B. *Fuzzy PID parameters gain scheduler*

The nonlinearity relationship between the parameter of IMC-PID and λ can be observed in Fig.6 to Fig.9. A popular approach is to approximate the nonlinear systems by linear systems through partitioning the nonlinearity into local linear parts.

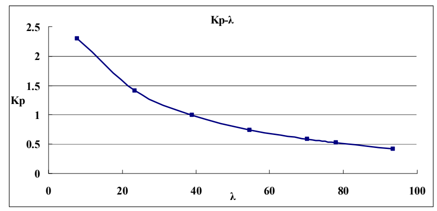

Fig.6 Relationship between K_i and λ

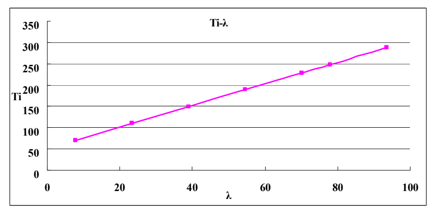

Fig.7 Relationship between T_i and λ

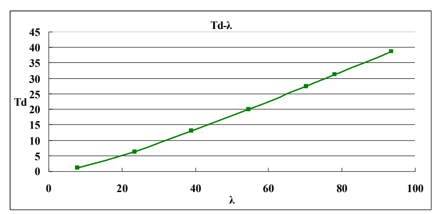

Fig.8 Relationship between T_d and λ

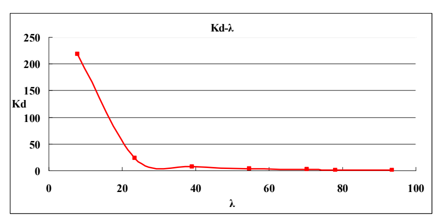

Fig.9 Relationship between K_d and λ

In the proposed method, η is devided into 7 sections: η=0.1,0.3,0.5,0.7,0.9,1,1.2. In each of the 7 sections, the relationship between the scheduler variable and each PID parameter is shown in Fig.10.

To deal with the nonlinear relationship between the parameter of IMC-PID and η, a gain scheduler is presented here. The core of the scheduler is a fuzzy system with the following inference rules.

IF η is H_n,

THEN $u_n = K_{pn}e + \frac{1}{\tau_{in}\times S}e + \frac{K_{dn}\times\tau_{dn}\times S}{\tau_{dn}\times S+1}e$ (8)

Where K_{pn} , τ_{in} ,K_{dn} and τ_{dn} are the linguistic values of PID parameters: proportional, integral , derivative lag constant and derivative time constant, respectively. The scheduling coefficient η, to be selected in accordance with the application of the scheduler, represents a change region and the linguistic term A_n is a fuzzy set that represents r region along the space of η.

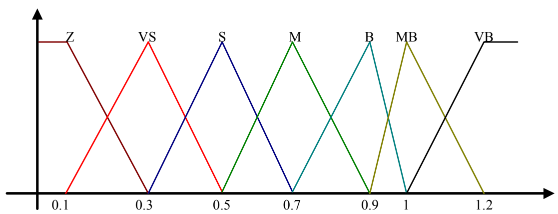

Fig.10 Membership functions for fuzzy adjusting coefficient η.

Assuming the scheduling variable η is in the overlap of partition j and j-1, the associated j and j-1 gain scheduler rules (membership functions) are active:

$$\mu_{H_{j-1}}(\lambda)+\mu_{H_j}(\lambda)=1 \tag{9}$$

Then, the controller parameters are scheduled as:

$$K_{pn}=(1-\mu_{H_j})K_p(j\text{-}1)+\mu_{H_j}K_p(j) \tag{10a}$$

$$\tau_{in}=(1-\mu_{H_j})\tau_i(j\text{-}1)+\mu_{H_j}\tau_i(j) \tag{10b}$$

$$K_{dn}=(1-\mu_{H_j})K_d(j\text{-}1)+\mu_{H_j}K_d(j) \tag{10c}$$

$$\tau_{dn}=(1-\mu_{H_j})\tau_d(j\text{-}1)+\mu_{H_j}\tau_d(j) \tag{10d}$$

Then, the IMC-PID controller parameters K_{pn} , τ_{in} ,K_{dn} and τ_{dn} can be adjusted online based on (10a)- (10d).

IV. RESULTS OF THE SIMULATION CAMPAIGN

In order to demonstrate its effectiveness, the proposed control scheme is compared with the IMC and the Specified Phase and Gain Margin (SPGM) method [3] in this section.

The system is represented by the transfer function:

$$G(S)=\frac{1.5}{(40s+1)^5} \tag{11}$$

This is a high-order inertia process. An approximate lower-order model must be built for such a high-order process when applying the IMC design. An identification procedure is used to obtain a FOPDT model. Many methods for the identification of a FOPDT transfer function can be chosen. Here, the relay feedback identification method is used to identify the FOPDT model [2] [9]. The obtained FOPDT transfer function is as follows:

$$G_1(S)=\frac{1.56}{(146.9s+1)}e^{-80.8s} \tag{12}$$

Within each partition, PID parameters are derived from Eqs.(6)~(11) by using the IMC-PID tuning method with corresponding η, which are listed in table Ⅱ.

TABLE Ⅰ TUNING VALUE OF IMC-PID UNDER DIFFERENCE SCHEDULING REGIONS

η	λ=ηθ	Kp	Ti	Td	Kd
1.2	96.979	0.40267	365.611	40.1293	0.00203
1	80.816	0.491855	315.182	32.3264	0.09091
0.9	72.734	0.547954	289.968	28.4613	0.17151
0.7	56.571	0.695121	239.539	20.842	0.4942
0.5	40.408	0.919473	189.109	13.4693	1.41159
0.3	24.245	1.303272	138.68	6.61222	5.17192
0.1	8.0816	2.109841	88.25104	1.154514	56.16684

First, a test is carried out by introducing a set-point change (0%~50%) in Fig.10. The process input is PV and output is OP. The line colors as listed in table Ⅲ. From the simulation results, it is found that the control quality of the FGS+IMC-PID is the best for not only the rising time but also the overshoot, settling time and steady error, while the classical IMC-PID (λ=1θ) gives longer settling time, and SPGM-PID even shows little oscillations.

A. *Robustness to Model Errors*

To test the robustness of the scheme, the model (11) is used with the controller parameters in table II, and three models in the robustness test are slightly different from the model (11), which are shown in 13(a), 13(b) and 13(c) respectively.

$$G(S)=\frac{1}{(10s+1)^3(40s+1)^2} \tag{13a}$$

$$G(S)=\frac{2}{(10s+1)^3(40s+1)^2} \tag{13b}$$

$$G(S)=\frac{1}{(60s+1)^3(40s+1)^2} \tag{13c}$$

TABLE Ⅱ. LINE COLOURS OF FIGURE 11-13.

Color	Line
Red	Process Variable of fuzzy IMC-PID controller
Blue	Process Variable of SPGM -PID controller
Green	Process Variable of IMC-PID controller
Yellow	Output of IMC-PID controller
Black	scheduling coefficient η
Purple	Output of SPGM -PID controller
Cambridge blue	Setpoint
Light Green	Output of fuzzy IMC-PID controller

The same PID parameters in Table II are employed in the robustness test. A 50% setpoint step is applied to each of the three models at the beginning until each of the model went steady. After that, each of the test models was changed back to the model (11).

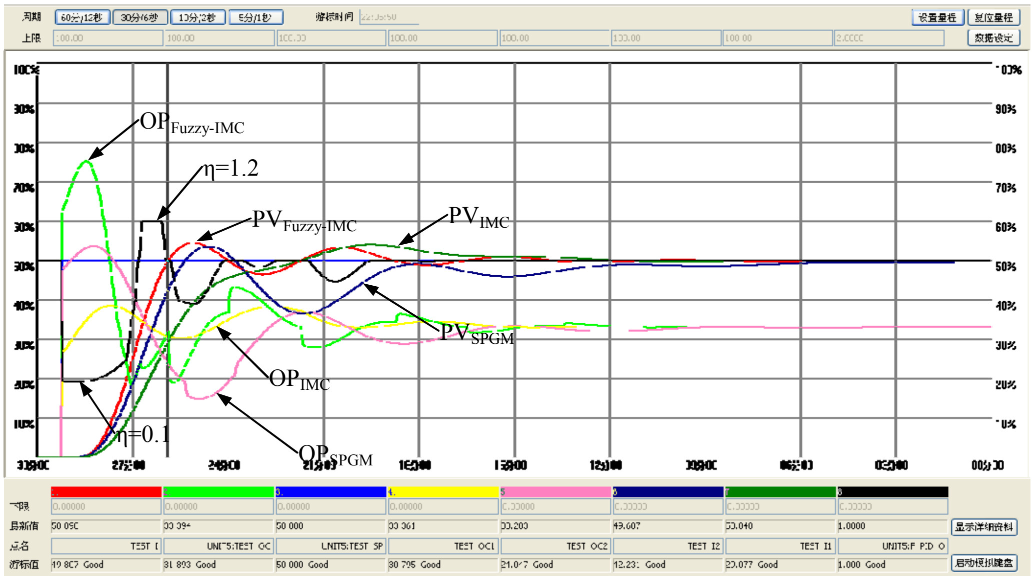

Fig.11. Set-point change

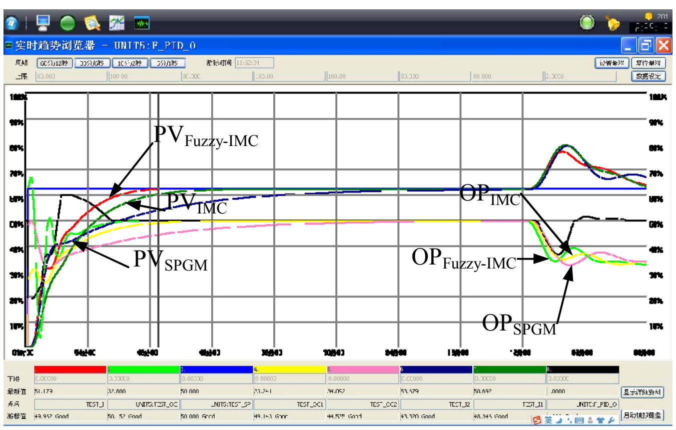

Fig. 12. System step responses when modeling errors in the time constant and static gain were introduced.

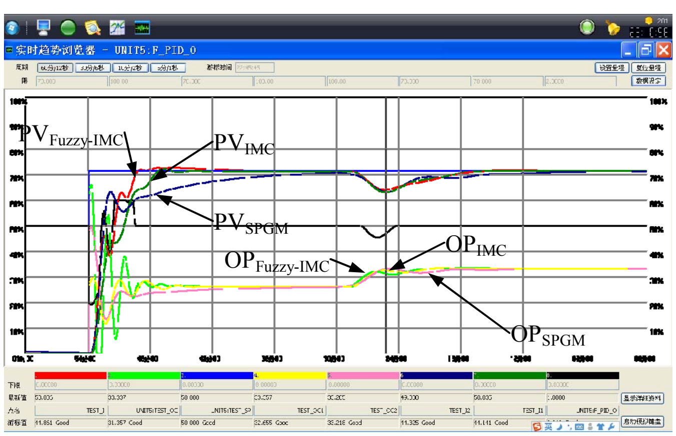

Fig. 13. System step responses when modeling errors in the time constant and static gain were introduced.

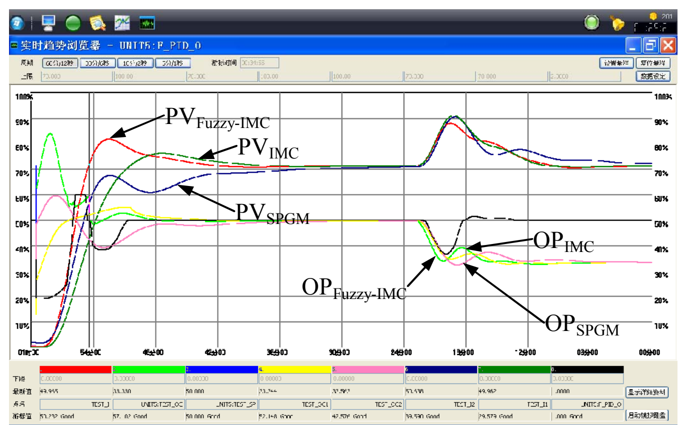

Fig. 14. System step responses when modeling errors in the time constant and static gain were introduced.

From the responses of (13a), the steady state gain and time constant are decreased, as shown in Fig. 12. From the response of (13b), the steady state gain is increased and the time constant is decreased, as shown in Fig. 13. From the response of (13c), the steady state gain is decreased and the time constant is increased, as shown in Fig. 14.

All of the three controllers are robust to the given modeling errors in the process static gain and time constant. It is seen that the FGS+IMC-PID controller reacts quickly, providing faster rising time and less overshoot than other controllers. The response with the SPGM-PID is sluggish with some fluctuation.

V. APPLICATION ON UNIT CONTROL

Based on the simulation study above, the proposed control scheme is realized by using the ABB Symphony-DCS and is developed for the boiler-turbine unit control system. Which has been successfully applied in Baolihua 4 ×300MW power plant in China.

A. Identifying the plant models

To design the IMC-PID controller for the boiler master control loop, we first use the relay feedback identification method to build the FOPDT model for the boiler master control loop.

Then, the FOPDT model of BM control loop at 270 MW loading conditions is derived as:

$$G_{BM}(S) = \frac{0.8}{(657s+1)} e^{-320s}$$

The FGS+IMC-PID tuning method has been used to set the parameters of the BM controller as table II after the identification procedure.

Table III TUNING VALUE OF BOILER MASTER CONTROLLER FGS+IMC-PID UNDER IMC-PID TUNING METHOD

H	Λ=ηθ	K_p	K_i	K_a	K_d
1.2	384	0.88645	0.08082	158.897	0.01234
1	320	1.07656	0.09375	128	0.44083
0.9	288	1.196169	0.101902	112.6957	0.728826
0.7	224	1.51002	0.123355	82.52632	1.525034
0.5	160	1.988715	0.15625	53.33333	2.79475
0.3	96	2.808303	0.213068	26.18182	4.99615
0.1	32	4.533642	0.334821	4.571429	9.431365

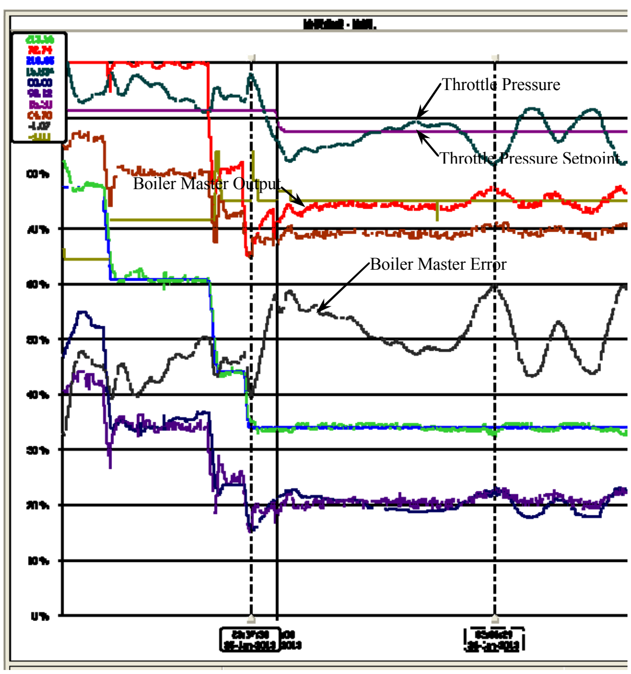

Fig. 14. Main process variables of the SPGM-PID

Figure 13 shows the operation result under the BM PID controller with SPMG tune method [4,5] when the unit load is changed from 260 mw to 210 mw at the rate of 4.5 mw/min. As it is seen from the operation curves, and there is a significant fluctuation in boiler parameters, throttle position and throttle pressure, for example, the error of the BM control loop reaches to 1 and throttle pressure surge reaches to 0.5 MPa.

Figure 14 shows the principal parameters of the boiler-turbine unit under the proposed FGS+IMC-PID on the BM control loop of unit control system. when the unit load is changed from 250 mw to 200 mw at the rate of 4.5 mw/min. The data shows that the main controlled variables of the unit are all kept near their set points, the error of the BM control loop is <0.2 and throttle pressure surge is <0.35 MPa.

From field tests, it can be seen that the proposed FGS+IMC-PID controller has the advantages of reducing the oscillation, overshoot, time lag and severe non-linearity in boiler-turbine unit controls. The FGS+IMC-PID controller described in this paper is realized by using the distributed control system (DCS), which has been successfully applied in the Baolihua power plant (4×300 MW) power plant.

VI. CONCLUSIONS

In this paper, a Fuzzy Gain Scheduling IMC-PID (FGS+IMC-PID) scheme is presented based on the fuzzy performance degree coefficient η. This adaptive scheme can be used to improve the performance and robustness of the classical PID controller. When compared to other PID tuning methods (IMC, SPMG), the new scheme gives the closed-loop response with less overshoot and shorter rising time. The control scheme using this method has been successfully applied and verified in commercial power plants. Field application shows that the proposed is accurate enough.

ACKNOWLEDGMENT

We would like to deep thank Prof. Weidong Zhang (Shanghai Jiaotong University) for helpful discussions on the IMC-PID control. This paper is partly supported by the National Science Foundation of China under Grants 61025016 and 61034008.

REFERENCES

[1] Astrom, K.J. and R.D. Bell (1993). A nonlinear model for steam generation processes. Proceedings *IFAC 12th Triennial World Congress. Sydney, Australia.* 649- 652.

[2] Gu, D. Y.; Y.C. Tang L.L. Ou and W.D. Zhang (2005). Relationship Between Two Typical Modeling Methods in Process Control and Its Application in Relay Feedback Autotuning. *Impulsive Dynamical Systems and Applications.* **3** pp *1650-1657*

[3] Li X. F. (2007). Application of The Fuzzy-PID to The Power Plant. *NAFIPS-2007.* 2007. pp 210-215.

[4] Li X. F. (2010). Intelligent Coordinated Control of Circulating Fluidized Bed Boiler. *NAFIPS- 2010,* 2010 pp 445-450.

[5] Li X. F., Zhang, W.D.. (2012). Coordinated Control of Circulating Fluidized Bed Boiler Based on the Fuzzy PID Control.. *NAFIPS-2012,* 2012. pp 16-22.

[6] Rivera, D. E., Morari, M., Skogestad, S., 1986, Internal model control. 4. PID controller design, *Ind. Eng. Chem. Res.*, 25 (1), 252–265.

[7] Tan W, Marquez HJ, Chen TW. Multivariable robust controller design for a boiler system. *IEEE Trans Control Syst Technol* 2002;10(5):735－42.

[8] Wang Q G, Zhang Y. Robust identification of continuous systems with dead-time from step responses[J]. *Automatica,* 2001, 37(3): 377-390.

[9] Yu, C.C. (1999) Autotuning of PID Controllers——Relay feedback Approach. *Springer-Verlag Berlin Herdelberg,* NY, 1999.

[10] Zhang, W.D. (2011) Quantitative Process Control Theory. CRC Press FL,USA 2011.

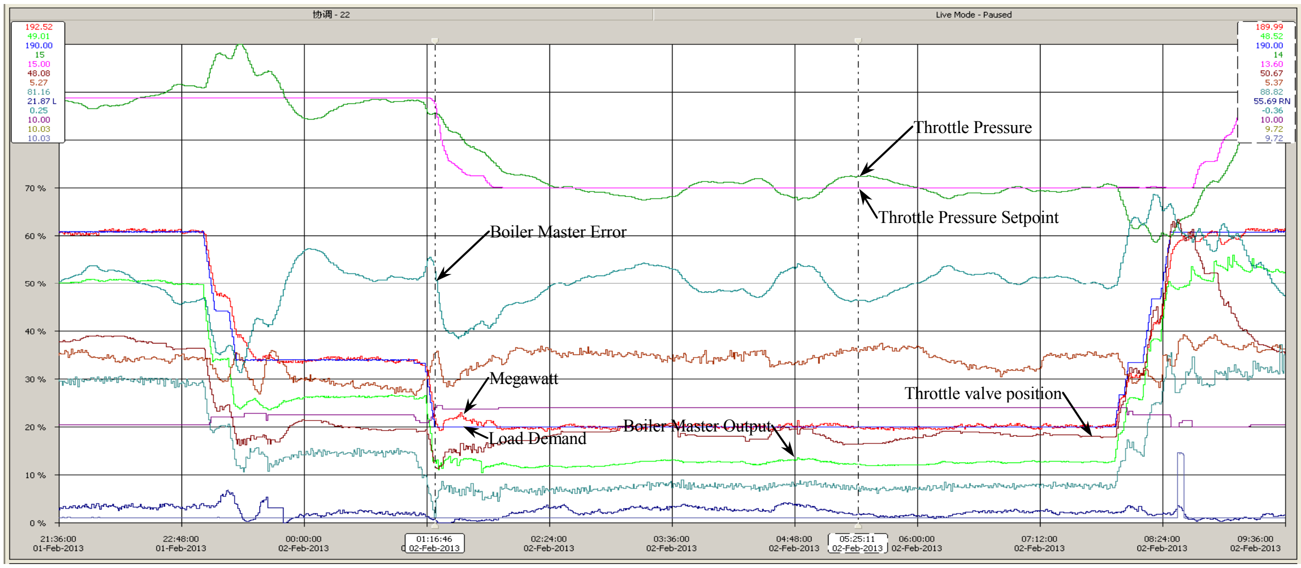

Fig. 15. Main process variables of TITO control loops under proposed autotune procedure