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Intelligent Tuning of the Two Degrees-of-Freedom Proportional-Integral-Derivative Controller On the Distributed Control System for Steam Temperature Control of Thermal Power Plant

Dong Hwa Kim, Won Pyo Hong and Seung Hack Lee

Abstract - In the thermal power plant, there are six manipulated variables: main steam flow, feedwater flow, fuel flow, air flow, spray flow, and gas recirculation flow. There are five controlled variables: generator output, main steam pressure, main steam temperature, exhaust gas density, and reheater steam temperature. Therefore, the thermal power plant control system is a multinput and output system. In the control system, the main steam temperature is typically regulated by the fuel flow rate and the spray flow rate, and the reheater steam temperature is regulated by the gas recirculation flow rate. However, strict control of the steam temperature must be maintained to avoid thermal stress. Maintaining the steam temperature can be dificult due to heating value variation to the fuel source, time delay changes in the main steam temperature versus changes in fuel flow rate, difficulty of control of the main steam temperature control and the reheater steam temperature control system owing to the dynamic response characteristics of changes in steam temperature and the reheater steam temperature, and the fluctuation of inner fluid water and steam flow rates during the load-following operation. Up to the present time, the Proportional-Integral- Derivtive Controller has been used to operate this system. However, it is very difficult to achieve an optimal PID gain with no experience, since the gain of the PID controller has to be manually tuned by trial and error. This paper focuses on the characteristic comparison of the PID controller and the modified 2-DOF PID Controller (Two- Degrees-Freedom Proportional-Integral-Derivative) on the DCS (Distributed Control System). The method is to design an optimal controller that can be operated on the thermal generating plant in Seoul, Korea. The modified 2-DOF PID controller is designed to enable parameters to fit into the thermal plant during disturbances. To attain an optimal control method, transfer function and operating data from start-up, running, and stop procedures of the thermal plant have been acquired. Through this research, the stable range of a 2-DOF parameter for only this system could be found for the start-up procedure and this parameter could be used for the tuning problem. Also, this paper addressed whether an intelligent tuning method based on immune network algorithms can be used effectively in tuning these controllers.

1. Introduction

Studies on the control of thermal power and combined plant have been popular for many years since these systems have been widely adopted as peak load candidates for electrical power generation [1]. The fully automatic start-up function and the fast run-up characteristics of the control systems have made them particularly suitable for peak-load lopping and standby power supply purposes. In the fossil-fired power plant, high-pressure and high temperature boilers are used for generation of electric power large capacity. Also, steam temperature deviation must be kept within $\pm 5°C$ in order to maintain boiler operating efficiency and equipment life time as well as to ensure safety.

The start up procedure stages for a mode thermal power turbine include warming up of the main steam pipeline, warming up of the turbine parts, turbine run-up, synchronization, and loading. So, the control in each step, from start-up to loading must be stable and safes [3]. Start-up and shutdown procedures of the steam temperature control in the electric power generation boilers are the most challenging problems when developing new control algorithms. The sequence of operations must be successfully performed to maintain steam temperature at the outlet of the superheater and the reheater regardless of the changes in the plant load, properties of the fuel, the conditions of the furnace through a sequence of safe states. At the same time, many variables must be monitored and controlled to ensure operational safety [3, 4]. Moreover, minimal time and energy losses during start up and run-up procedures would be desirable.

Additional problems are involved when starting up or shutting down certain components within a larger power station. Because of the fuel situation, the number of coal-fired power plants has been increasing each years, and their steam temperature dynamics and their interconnections between components occur not only through the electric network, but also on the heat exchange side, i.e. steam flows are affected largely by the properties of the coal and furnace conditions such as the fouling or seasoning of boiler tubes. Up to now, a Proportional – Integral – Derivative (PID) controller has been used in the steam tempera-

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ture control of boiler. However, it cannot effectively control such a complicated or fast running system, since the response of a plant depends on only the gain P, I, and D. Obtaining the linear algorithm may be problematic when controlling a plant with highly nonlinear dynamic characteristics. In addition, steam in the thermal power plant must be produced to certain specifications during start up and during large and fast changes of the plant load. The PID controller cannot effectively meet the requirements of both the set-point-following and disturbance rejection. When using a PID controller, the plant is generally controlled without consideration of disturbance rejection. A industrial experience is required for higher automatic tuning; the PID controller is usually poorly tuned in practice [4]. Failure to tune in control will cause an inevitable plant shutdown, and a loss of production and considerable damage to the plant may result. An effective control is required to maintain the system reliability and stability following a system disturbance [2, 4].

However, any new theory should be proven on the physical plant or equipment before being used on the real plant to ensure safety and reliability.

The 2-DOF PID controller is well known for its robustness, because it is designed to perform two functions: 1) set point following, 2) disturbance rejection. However, since its tuning method and performance in a control system depend on the system used, the tuning in each system must be studied. This paper focuses on the characteristic comparison of the PID controller and the modified 2-DOF PID controller on a DCS to design an optimal controller that can be operated on a thermal generating plant in Korea. This paper also addresses whether an intelligent tuning method based on a immune network algorithms can be used effectively in tuning these controllers.

2. Control Characteristics of Thermal Power Plant for Controller Design

2.1 Control Characteristic in the Thermal Power Plant

The boiler for a thermal power plant is made by the Hanjoong Co. in Korea, which is a typical 500MW once-through supercritical unit. Steam temperature control, one of many control loops in the thermal power plant considers the most difficult and requires attention [2].

In the coal-fired thermal power plant, there are six manipulated variables: main steam flow, feedwater flow, fuel flow, air flow, spray flow, and gas recirculation flow. In addition, there are five controlled variables; generator output, main steam pressure, main steam temperature, exhaust gas O_2 density, and reheater steam temperature [4]. Therefore, the coal-fired power plant is a multi-input and multi-output system, which must alter the generator output in response to changes in the load demand dictated by the DCS in a central load dispatching office.

Fig. 1 shows a functional diagram of the steam temperature system for the Boryong power plant and is composed of three subsystems. The first is a feedforward system, which feedforwardly controls the manipulated variables in accordance to a load demand signal. The second subsystem is a feedback-control system, i.e., a proportional plus integral (PI) control system, which generates signals to modify the manipulated variables on the basis of feedback signals from the controlled variables. The third subsystem is a subloop control system which adjusts the manipulated variables according to the feedforward and the feedback control signals.

In the thermal power plant, strict control of the steam temperature is critical to maintain safety and avoid thermal stress, which leads to premature failure of the steam turbines. The main steam temperature typically is regulated by the fuel flow rate and the spray flow rate, and the reheater steam temperature is regulated by the gas recirculation flow rate. However, the following problems have been identified in steam temperature control [1, 13].

(1) The heating value of coal, which cannot be measured on-line, varies according to the coal source. The coal source changes within a period ranging from a week to a month and the heating value of the coal can vary from approximately 90% to 110% of a typical value during the course of a day. Furthermore, process characteristics change slowly during a long operation. These factors make it difficult to provide accurate control of the heat input to the boiler.

(2) Since the coal pulverizing process proceeds slowly and since the heat capacity of coal-fired plants is larger than that of oil or gas burning plants, the time delay of changes in main steam temperature versus the changes in fuel flow rate greatly exceeds the delay experienced in oil or gas burning plants. That is, accurate steam temperature control is very difficult to attain during rapid load changes. If the load changes rapidly, the conventional PID controller adjusts the input variables to values corresponding to the boiler load, causing steam temperatures deviation from its set point (more than $\pm 5°C$). Therefore, it is not easy to compensate for steam temperature deviation during start up and rapid load changes. The terminology is somewhat specialized to make the control easier.

(3) The main steam temperature control system and the reheater steam temperature control system may interfere with each other. This means that overall temperature control comprises a multi-input and output interference system. Hence, it is difficult to control well both the main steam temperature and the reheater steam temperature.

(4) Flow rates in water and steam fluctuate widely during load-following operation. For example, both the time constant and the gain vary by more than a factor of two during a load-following operation.

(5) Characteristics of the process may change due to

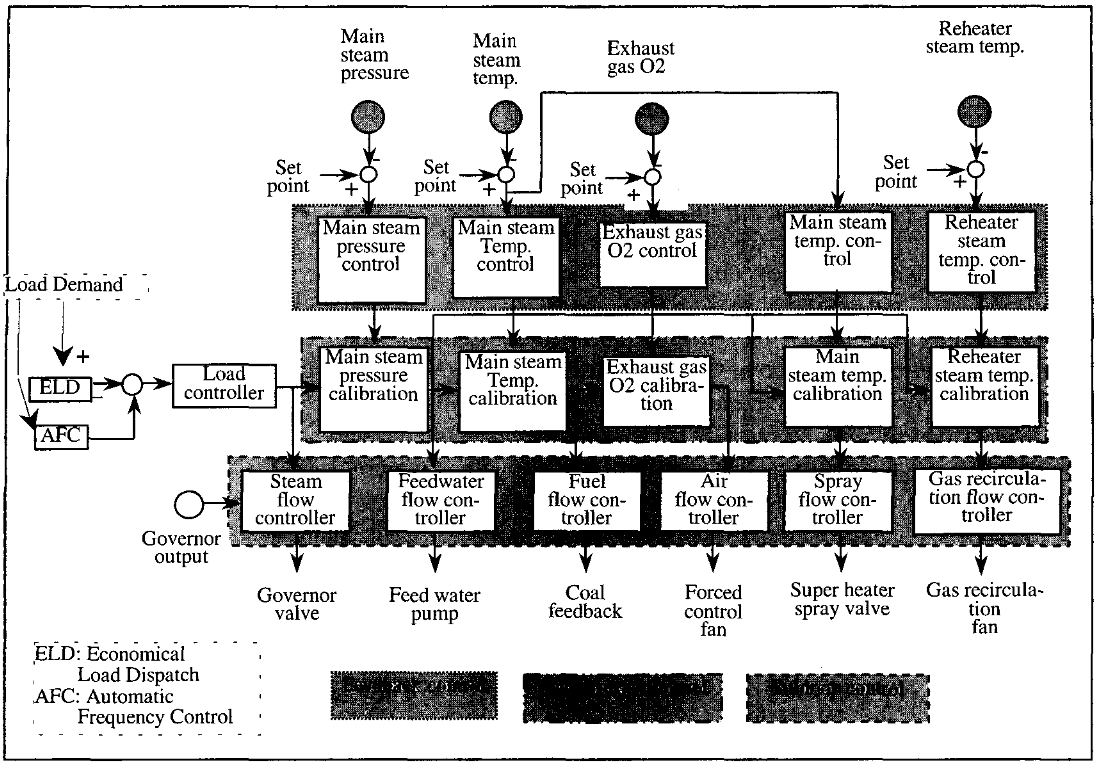

Fig. 1 Functional diagram of thermal power plant.

fouling in the hot gas flow system. Figs. 4-6 are block-diagrams restructured from Fig. 2 for the 2-DOF PID controller design.

2.2 Steam Temperature Control Approaches in Power Plant Boiler

In the power plant, the strategy used for the control of steam temperature for power plant boilers is normally recommended by the boiler manufacturer. The normal steam temperature control requirement has to sustain the temperature within $\pm 5°C$. Figs. 2 and 3 show two methods of controlling the superheater temperature using a water spray in the power plant. That is, in typical steam temperature control approaches, some form of feedforward control, cascade control, or a combination of these has been used.

Fig. 2 shows the application of a feedforward and feedback strategy for temperature control using a super heater spray. In calibrating and tuning this system, the relationship between the air flow rate and the spray water control valve input signal is determined by steady state testing at the design steam temperature and while operating at different boiler steam flow rates. When this relationship is known, the air flow signal is scaled and functionally adjusted by modifying the f(x) function and by changing the input gain of the summer f(x).

Fig. 3 shows an alternate cascade control for reheater steam temperature. Figs. 4 - 6 represented the control loop of the platon super heater, the super heater temperature control loop, and the hanger tube temperature control loop restively, Fig. 2, Fig.4 is a cascade loop with PID3 and PID4. F(*x1*) has a feedword function. On the other hand, in Fig. 5, PID1 and PID2 are loops for cascade control, and Fig. 6 is composed of feedforward, cascade, and feedback loops.

The time constants and transfer functions for the steam-temperature systems are given in the following expressions [4].

$$\frac{Steam\ temperature}{Spray\ flow}=\frac{0.72}{(1+85P)^3}\ {}^oC\ /\ percent\ input$$

$$\frac{Steam\ temperature}{Firing\ rate}=\frac{5.4}{(1+110P)^2}\ {}^oC\ /\ percent\ input$$

From these equations, gauging the problems of controlling the steam temperature, notably the very long time constants of the system will be possible.

2.3 Superheated Steam Temperature Control

Fundamentally, the temperature of the final superheated steam is a function of the boilers firing rate and the steam flow, and of the design of the heating surfaces and the plant generally. In practice, however, the steam temperature of an operating boiler will be affected by the cleanliness of the tube banks and, consequently, will tend to be higher immediately after soot-blowing has been carried out. The control systems for the final superheated steam temperature in boilers rely almost exclusively on attemperators-usually of the spray type. A cascade control system is used to overcome the long time constants of the secondary superheater in steam temperature control.

The temperature of the steam leaving the secondary superheater is controlled by a three-term controller as shown in Fig. 5. Since boiler-plant measured variables tend to be very noisy, much of the noise will be fed to the controller. Therefore, excessive filtering would degrade the quality of control and any derivative action will cause the output to become unstable.

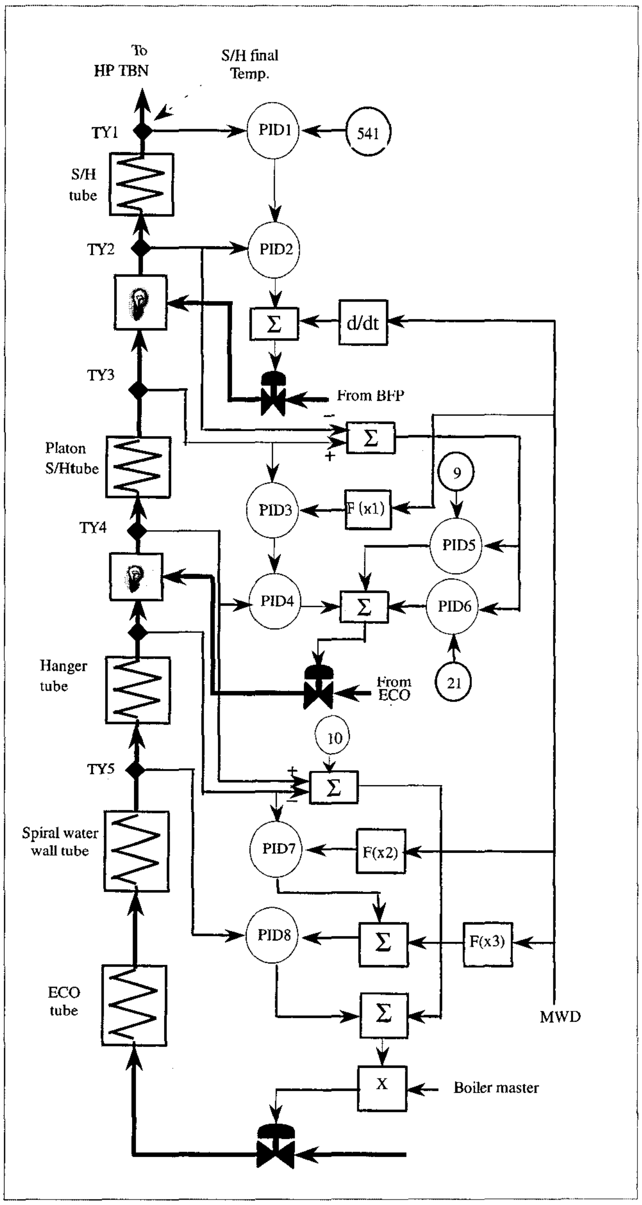

Fig. 2 Shematic diagram of S/H heater steam temperature control system in the power plant.

2.4 Multistage Superheaters for Steam Temperature Control

In boilers with several stages of superheating and employing cascade systems for each section as shown in Fig. 2, spray attemperators are normally provided between the major superheating banks. The operation of each individual cascade system is broadly similar to the simple loop. However, the secondary superheater system includes some notable provisions. The first key condition in this system is to generate the desired value for the secondary superheater outlet temperature controller from the outlet of the final steam temperature controller, PID1. This is because the final temperature controller output signal can determine the optimum temperature conditions throughout the superheater string.

The second point is the maximum selector block, A, interposed between the first-stage main controller, PID3 and its slave, PID4. This block also receives a signal derived from the drum pressure via a function block, which translates the measured pressure into the equivalent saturation temperature and adds the required safety margin to the result. This arrangement prevents the slave from receiving a de sired temperature signal that is too close to the saturation temperature, and therefore prevents the chilling effect referred to earlier [13].

Finally, the system incorporates an air flow feedforward sinal an attempt to optimize response to load changes.

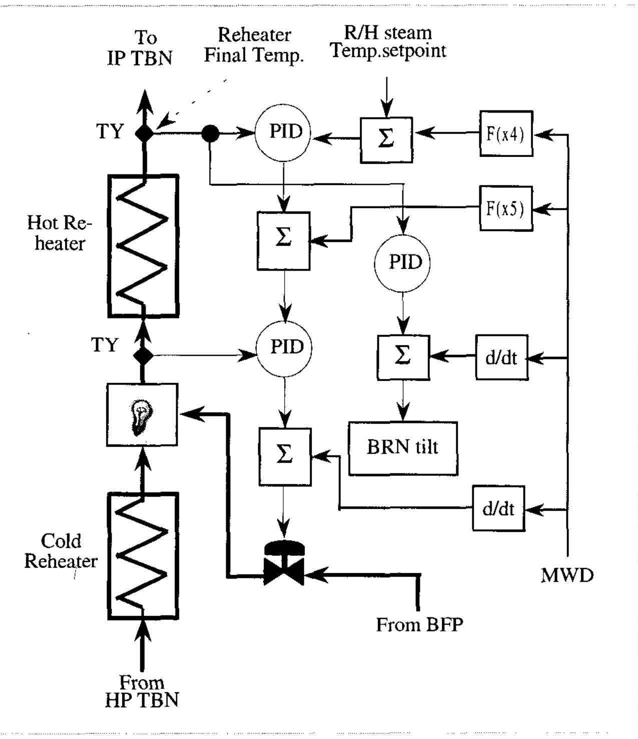

Fig. 3 Shematic diagram of reheater steam temperature control system in the power plant.

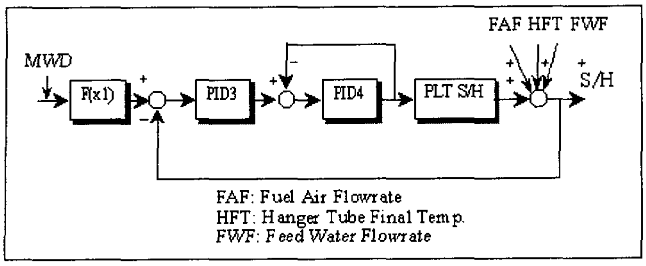

Fig. 4 Block diagram of platon super heater temperature control system.

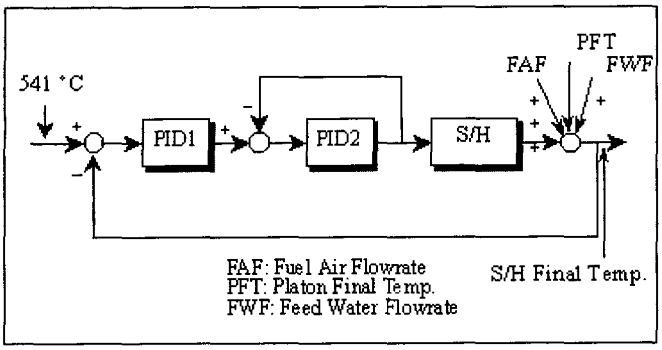

Fig. 5 Block diagram of super heater temperature control system.

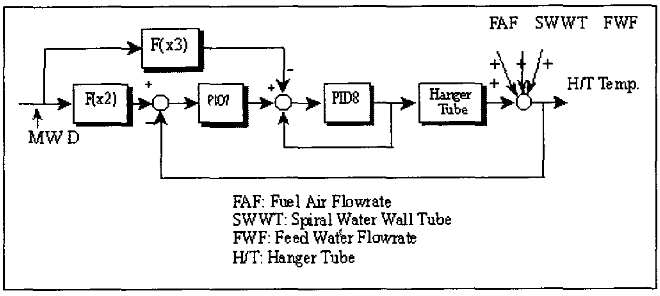

Fig. 6 Block diagram of hanger tube temperature control system.

2.5 Reheated Steam Temperature Control

The reheater control system of Fig. 3 displays many of the difficulties of the superheat counterpart. For example, the time constants and transfer functions are given by a similar equation [1], [13] :

$$\frac{Steam\ temperature}{Firing\ rate} = \frac{7.2}{(1+110P)^2}\ {}^{o}C/\ percent\ input.$$

Nevertheless, because of the lower steam pressure in the reheater system, the thermodynamic conditions are quite different from those of the superheater. Spraying water into the reheat circuit has an adverse effect on the cycle efficiency, and therefore it is common to reserve operation of reheat sprays for emergency duty only, with the reheated steam temperature being controlled primarily by adjustment of the hot gas flows over the tubes. In many plants, separate gas recycling fans are specifically provided for this purpose.

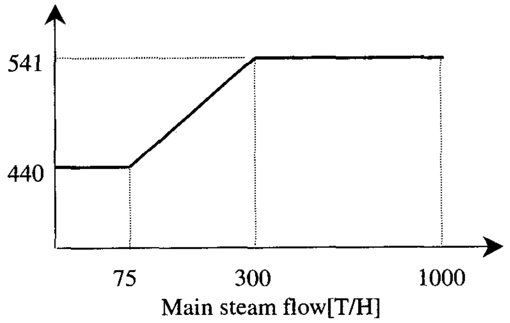

Fig. 7(a) Function generator, F(x1)

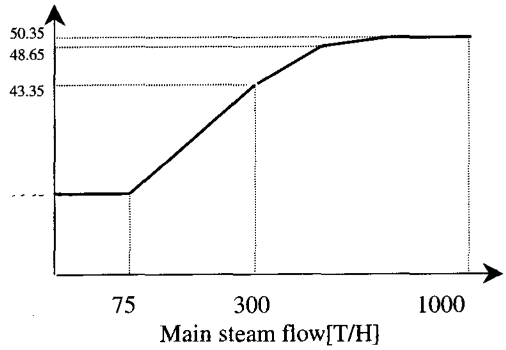

Fig. 7(b) Function generator, F(x2)

Moreover, because of the large pressure drop between the feed pump discharge and the reheat system, the reheat spray-water supply must be taken from a point before the main boiler-feed pumps. To control the hot gas flows, two separate sets of dampers are sometimes employed, one in the path of the gases flowing over the superheater banks, the other controlling the gases flowing over the reheater banks. To protect the plant against over pressurization, these damper sets are controlled so that one set must be fully open before the other set can begin to close. Therefore, in this paper, damper opening is considered the same disturbance or noise as the Fuel Air Flowrate (FAF).

3. 2-DOF PID Controller Design for the Thermal Power Plant

3.1 Problem of the PID controller on the Steam Temperature Control System of the Thermal Power Plant

The PID controller has been widely used due to its simplicity and robustness in chemical process, power plant, and electrical systems. Its popularity is also due to easy implementation of hardware and software. However, using only the P, I, D parameters, it is very difficult to control a plant with complex dynamics, such as large dead time, inverse response, and highly nonlinear characteristics. Since the PID controller is usually poorly tuned, a higher of degree of experience and technology is required for tuning in the actual plant [5].

Table 1 P, I, D gain PID1 and PID2 controller for operation of the power plant.

PID1					PID2				
MW (%)	P (Multiple)	MW (%)	I (Multiple)	D	MW (%)	P (time)	MW (%)	I (%)	D
30	0.7	30	0.2	0	30	1.0	30	1.0	0
50-100	0.2	50	0.2	0	65	2.2	65	2.2	0
		75	0.3	0	75	2.5	75	2.5	0
		100	0.3	0	100	3.0	100	3.0	0

Table 2 P, I, D gain of PID3 and PID4 controller for operation of the power plant.

PID3					PID4			F(x)	
MW (%)	P (Multiple)	MW (%)	I (Multiple)	D	P (time)	I (%)	D	MW (%)	°C
30	2.0	30	0.2	0	3.0 (All load)	2.0 (All load)	0 (All load)	0	505
50	3.0	50	0.4	0				30	507
75	4.0	75	0.4	0				50	510
100	4.0	100	0.4					100	517

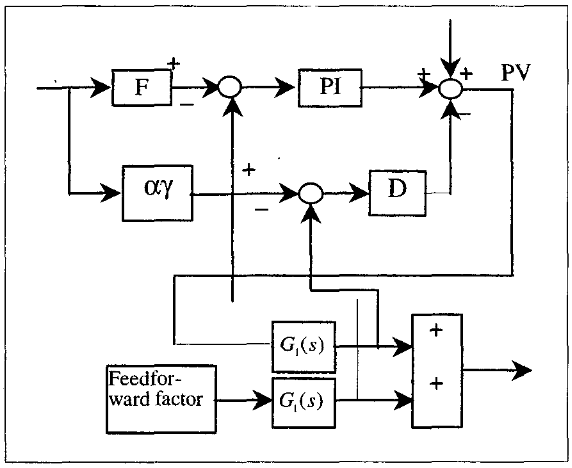

Fig. 8 Block diagram of the design principle of the 2-DOF PID controller with a combined 2-DOF parameter for the thermal power plant.

There are many well known PI and PID tuning formulas for stable processes. However, PID tuning formulas for unstable processes or complex plants are less common.

Up to this time, many sophisticated tuning algorithms have been tried an attempt to improve the PID controller performance under such difficult conditions since the control performance of the system depends on the P, I, D parameter gains.

3.2 Design Principle and Advantage of the Modified 2-DOF PID Controller for the Thermal Power Plant

This type of the 2-DOF PID controller has a combined parameter for a 2-DOF function as shown in Fig. 8. The transfer functions between process value *PV(s)* and settling value *SV(s)*, and between process value *PV(s)* and disturbance *DV(s)* are given in the following equations, respectively:

$$G_{PVDV}(\mathrm{s}) = \frac{PV(s)}{DV(s)} = \frac{G_d(s)}{1+K_p\left(1+\frac{1}{T_i s}\right)\gamma} \tag{1}$$

$$G_{PVSV}(\mathrm{s}) = \frac{PV(s)}{SV(s)} = \frac{\alpha K_p\left(1+\frac{1}{T_i s}\right)\left(\frac{1}{1+\beta T_i s}\right)+\left(\frac{\beta K_p K_d s}{1+\eta T_d s}\right)}{1+K_p\left(1+\frac{1}{T_i s}\right)\gamma} SV \tag{2}$$

$$G_{PVG1}(s) = \frac{\left(\frac{\beta K_p K_d s}{1+\eta T_d s}\right)}{1+K_p\left(1+\frac{1}{T_i s}\right)\gamma} G_1(s) \tag{3}$$

where, the filter transfer function is $F(s)=\frac{1}{1+\beta T_i s}$, the PI controller transfer function is $PI(s)=K_p\left(1+\frac{1}{T_i s}\right)$, and the D controller transfer function is $D(s)=\frac{K_p T_d s}{1+\eta T_d s}$. In equation (1), the numerator has a similar function to that of the conventional PID controller. That is, if the proportional gain K_p goes to a greater value, the efficiency of disturbance G_d is smaller. However, equations (2) and (3), the process value *PV(s)* and the plant $G_1(s)$ depend on the two degrees parameter α, β, γ. The proportional gain could also be affected by the parameter α, β, and γ given for the two degrees function. Since the disturbance can be reduced by gains K_p, T_i, and γ the process value PV and the plant $G_1(s)$ are effectively controlled by the two degrees parameter α, β, γ. Then, a 2 - DOF PID controller can perform the two degrees of function, completely. The result of this arrangement distinguishes it from the conventional arrangement method. A detailed description is given in the simulation section.

3.3 Performance Comparison of the Designed Controller on the Thermal Power Plant

The performance of the controller should be proven through running on actual plant or by a simulation and mathematical analysis method after design. This paper uses the transfer function and operating data of the generating plant to compare characteristics or the conventional PID and the modified 2 - DOF PID controller suggested in this paper. Generally, the transfer function is given by modeling. However, this paper obtained the transfer function from operating data acquired by the data acquisition system. The detailed advantages and characteristics will be suggested in the Section 5.

4. 2-DOF PID Controller Tuning by Immune Algorithms

The coding of an antibody in an immune network is very important because a well designed antibody coding can increase the efficiency of the controller. As shown in Fig. 9, there are three types antibodies in this paper: 1) antibody type 1 is encoded to represent only P gain in the PID controller; 2) antibody type 2 is encoded to represent I gain; 3) antibody is encoded to represent D gains. The value of the k locus of antibody type 1 shows P gain allocated to route 1. That is, the value of the first locus of antibody type 1 means that P gain allocated to route 1 is obtained by 20 [11, 12].

P	20	9	8	•••	7.5	5
I	20	3	8	•••	2.5	2
D	10	2	1	•••	1.5	1

Fig. 9 Allocation structure of P, I, D gain in locus in antibody.

On the other hand, the k locus of antibody 2 represents I gain for tuning of the PID controller. Here, the objective function can be written as follows.

$$\delta_i = \sum_{n=1}^{z} \left\{ \left(L_n - L_n^{object} \right) \right\}^2 + \zeta f_n$$

$$L_n = \sum_{i=1}^{P} \left(R_i I_{i,n} \right)$$

$$f_n = \begin{cases} 0 : L_n \le L_n^{\lim it} \\ 1 : Otherwise \end{cases} \tag{4}$$

where, δ_i : objective function

z: the number of processes for obtaining an optimal PID gain

L_n : optimal level in process for selection of an optimal gain

L_n^{object} : target optimal value in process for selection of an optimal gain

ζ : penalty constant

f_n : penalty function

P: the number of route for selection of an optimal gain

R_i : gain level in route i

$I_{i,n}$: subsidiary function

$L_n^{\lim}$: limit speed in PID gain

This algorithm is implemented by the following procedures.

[step 1] Initialization and recognition of antigen: The immune system recognizes the invasion of an antigen, which corresponds to input data or disturbances in the optimization problem.

[step 2] Product of antibody from memory cell: The immune system produces the antibodies that were effective to kill the antigen in the past. This is implemented by recalling a past successful solution from memory cell.

[step 3] Calculation of Affinity between Antibodies: The affinities $m_{\alpha\beta}$ obtained by Equation (4) and the affinity $m_{\varphi\alpha}$ using Equation (5) are calculated for searching a optimal solution.

[step 4] Differentiation of lymphocyte: The B - lymphocyte cell, the antibody that matched the antigen, is dispersed to the memory cells in order to respond to the next invasion quickly.

[step 5] Stimulation and suppression of antibody: The expected value η_k of the stimulation of the antibody is given by

$$\eta_k = \frac{m_{\varphi k}}{\sigma_k} \tag{5}$$

where σ_k is the concentration of the antibodies. The concentration is calculated by affinity based on phenotype but not genotype because of the reduction of computing time. So, σ_k is represented by

$$\sigma_k = \frac{sum\ of\ antibodies\ with\ same\ affinity\ as\ m_{\varphi k}}{sum of\ antibodies}. \tag{6}$$

Using equation (6), a immune system can control the concentration and the variety of antibodies in the lymphocyte population. If antibody obtains a higher affinity against an antigen, the antibody stimulates. However, an excessive higher concentration of an antibody is suppressed. Through this function, an immune system can maintain the diversity of searching directions and a local minimum.

[step 6] Stimulation of Antibody: To capture the unknown antigen, new lymphocytes are produced in the bone marrow in place of the antibody eliminated in step 5. This procedure can generate a diversity of antibodies by a genetic reproduction operator such as mutation or crossover. These genetic operators are expected to be more efficient than the generation of antibodies.

5. Simulations and Discussions

5.1 Transfer Function of the Thermal Power Plant by Operating Data

Fig. 10 shows the data acquisition system for acquiring the transfer function. The desired curve is achieved from running power plant data in the data file and is compared with the curve by the transfer function calculated. Fig. 12

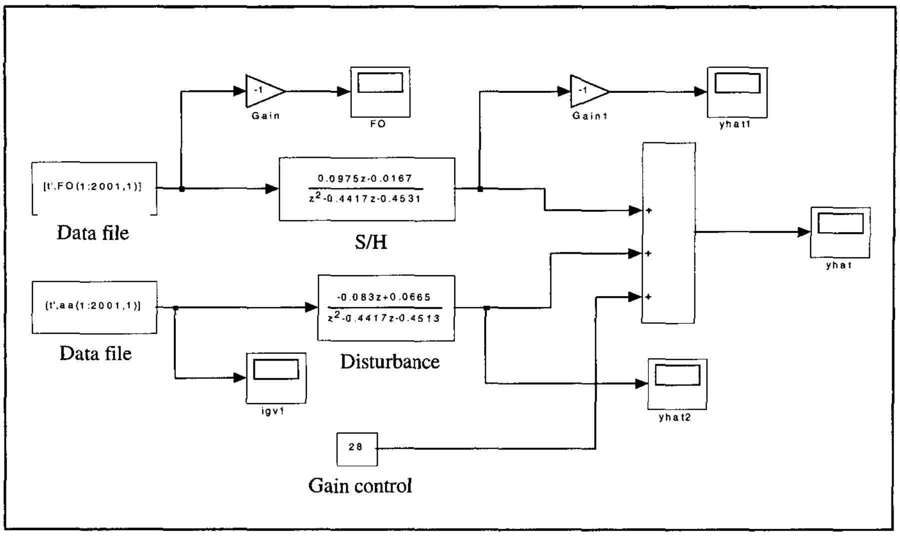

Fig. 10 Data acquisition for the power plant.

represents the curve obtained by the transfer function and operating data during start-up and running procedures. Both curves show a coincidental shape. This characteristic of the curve reflects the accuracy of the transfer function acquired from the data acquisition system.

5.2 The Characteristic of the PID Controller on the Thermal Power Plant

To observe the characteristic and problems of the PID controller used in the power plant, which is manually tuned by operator, this paper simulated using the transfer function and operating data of the power plant. Figs. 13 and 14 represent the responses of the PID controller on P=2.3, I=0.2, and D=0. When there is no disturbance, the steam temperature curve, FF, follows the controller signal, FS. However, in Fig. 15, the control loop that considers the effect of gas temperature disturbance indicates that the steam temperature FF, do not follow the controller signal, FS. This result shows that the influence of temperature variation (disturbance) is important to this stability of the power plant control. This means that if the PID controller is used in the start-up and running of a power plant, the control response cannot has a satisfactory result when there is a disturbance.

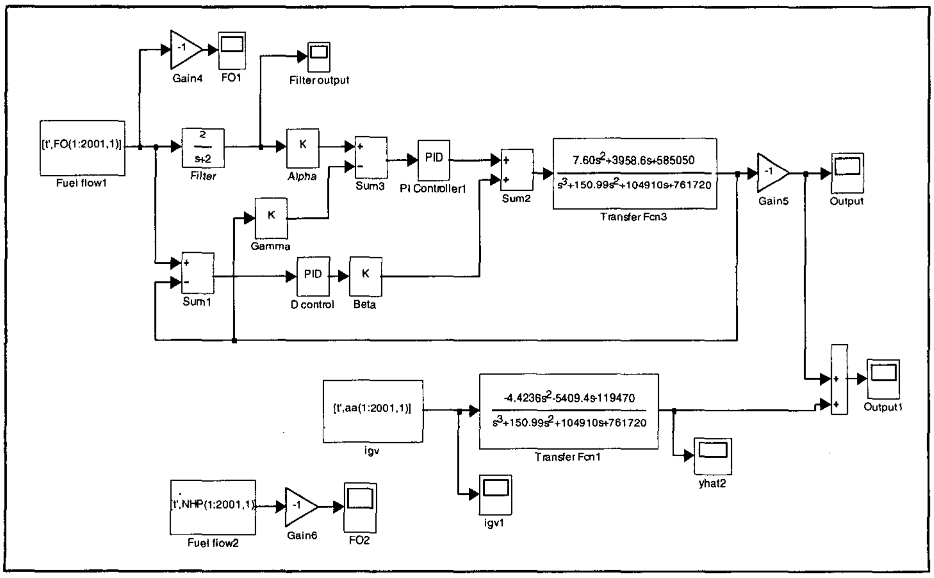

Fig. 11 Modified 2-DOF PID Controller with the 2-DOF parameter in the power plant.

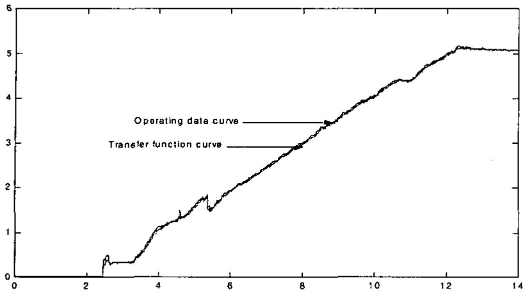

Fig. 12 Operating data curve and transfer function curve.

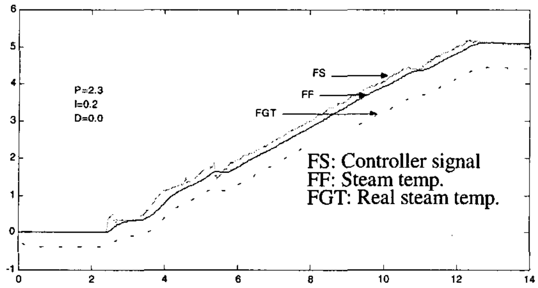

Fig. 13 Steam temperature response to ramp input on the PID controller without of a gas temperature effect (P=2.3, I=0.2, D=0).

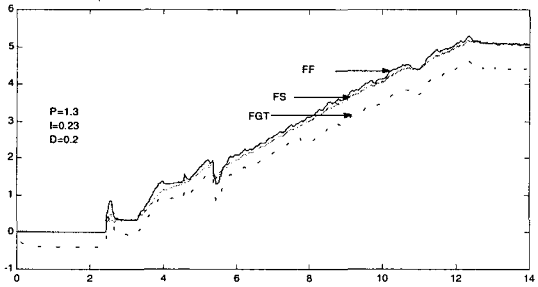

Fig. 14 Steam temperature response to ramp input on the PID controller without gas temperature effect (P=1.3, I=0.23, D=0.2).

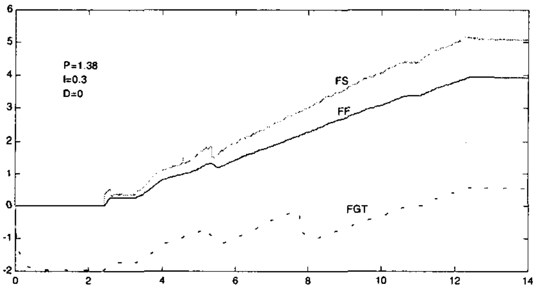

Fig. 15 Steam temperature response to ramp input on the PID controller with gas temperature effect 3°C (P=1.38, I=0.3, D=0).

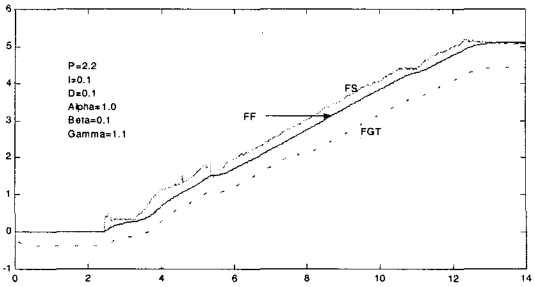

Fig. 16 Steam temperature response to ramp input P=2.2, I= 0.1, D=0.1, α=1.0, and β=0.1, on γ=1.1 of the modified 2-DOF PID controller with disturbance of gas temp.

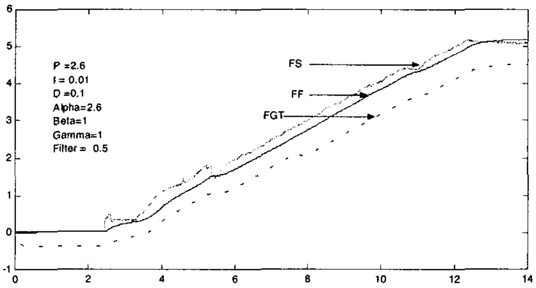

Fig. 17 Steam temperature response to ramp input on P=2.6, I=0.01, D=0.1, α=2.6, β=1, and γ=1 of the modified 2-DOF PID controller with disturbance of gas temp.

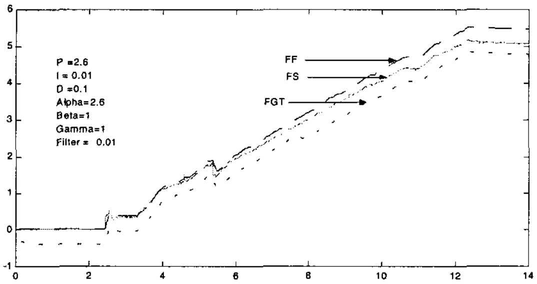

Fig. 18 Steam temperature response to ramp input on P=2.6, I=0.01, D=0.1, α=2.6, β=1, and γ=1 of the modified 2-DOF PID controller with disturbance of gas temp, and feedwater flowrate variation F=1.

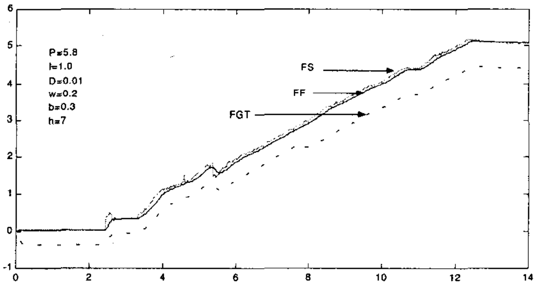

Fig. 19 Steam temperature response to ramp input on P=2.2, I=0.2, D=0.01, w=0.2 (air flow), b=0.3 (feedwater variation), and h=7 (hanger tube temp.) of the modified 2-DOF PID controller with 7°C disturbance of gas temp.

5.3 The Characteristic of Modified 2-DOF PID Controller on the Thermal Power Plant

Figs 16 - 21 represent the result of simulation using the modified 2 - DOF PID controller designed in this paper. The design conception of a 2 - DOF PID controller was suggested for a general plant by some researchers [4]. However, its tuning method should be studied to acquire a more stable response and operation. This paper designed the 2 - DOF PID controller for the power plant through modification from a general 2 - DOF PID controller. As it can be seen in Figs. 2 and 3, number of PID controllers are used for structuring cascade and feedforward loops for the required steam temperature control in the power plant and the gain of controllers depends on the variation of MWD (Mega Watt Demand: load variation) as shown in Tables 1 and 2. Therefore, the function curve of Fig. 7 is used for the required response. In a another words, the tuning method and procedures are very difficult and complicated.

To avoid this difficult tuning procedure and control loop, a simple control system was suggested through the 2 - DOF PID controller.

Figs. 16 - 20 show the results of the application of the 2 - DOF PID controller designed in this paper to the power plant shown in Fig. 8.

To obtain the effect of the change of each parameter of the modified 2 - DOF PID controller, was studied the response on the generating system when each parameter was changed.

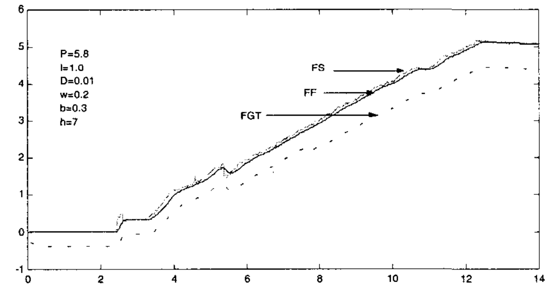

Fig. 20 Steam temperature response to ramp input on P=2.2, I=0.2, D=0.01, w=0.2 (air flow), b=0.3 (feedwater variation), and h=7 (hanger tube temp.) of the modified 2-DOF PID controller.

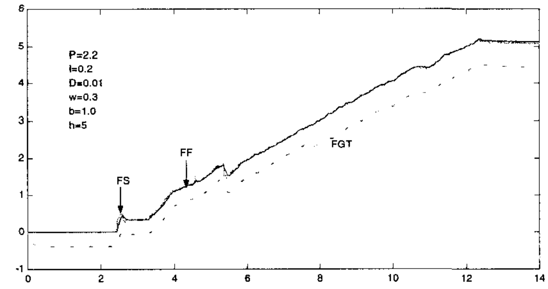

Fig. 21 Steam temperature response to ramp input on P=2.2, I=0.2, D=0.01, w=0.3 (air flow), b=1.0 (feedwater variation), and h=5 (hanger tube temp.)by the modified 2-DOF PID controller.

Figs. 16-17 show the characteristic of the change of parameter α, β, and γ in the modified 2 - DOF PID controller. In Figs. 16-17, the result of the steam temperature control shows a satisfactory response using tuning 2 - DOF parameters α, β, and γ even if gas temperature disturbance varied from 3°C to 5°C.

On the other hand, Figs 18 - 21 illustrate the result of simulation when other disturbances such as FWF, AFR, and gas temperature in steam control. Many kinds of disturbances are in the control loop but a satisfactory response is acquired.

5.4 Tuning of the 2-DOF PID Controller by Immune Algorithms

In this paper, the immune network algorithm is used to tune the modified 2 - DOF PID controller. Figs. 22 - 30 show the proposed control system in this paper, as some overshooting in the response of the PID controller tuned by Zielgler-Nichols shown in Fig. 22. However, Fig. 23 - 30 and Table 1 reveal that the variety of PID parameter can be obtained by the immune system.

Fig. 23 represents a comparative response to minimum values of parameters P, I, and D after learning when the learning range of parameters in the immune network is 20 (=P=I=D), 10 (=P=I=D), and 5 (=P=I=D), respectively.

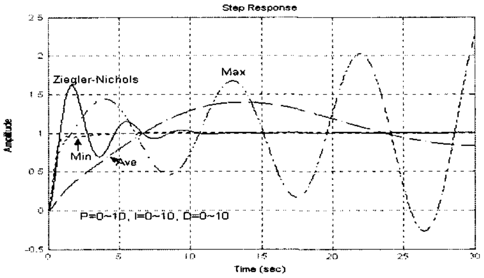

Fig. 22 Response to minimum values on parameter learning of immune network.

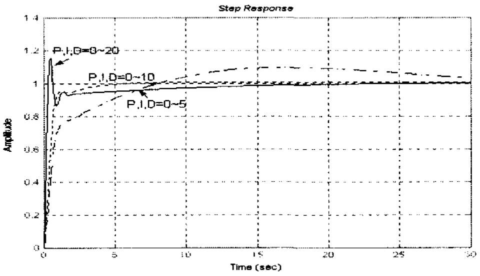

Fig. 23 Response to minimum values on parameter learning of immune network. (P=20, I=10, D=10)

On the other hand, Figs. 24 and 25 are the minimum and average response when P is varied and I, D are fixed as 10 and 20. Figs. 26 - 31 represent when P and I are is varied and only D varies.

5.5 Relationship Between 2-DOF Parameter and Immune Network

In this study, the relationship between the initial setting values for learning and P, I and D gain after learning by each cell in the immune system is not revealed clearly as shown in Fig. 23 - 31 and Table 1. However, since there are variations in PID parameters to a different initial value of learning, there could be some relationship between both parameters. Therefore, it is necessary to study this rule further.

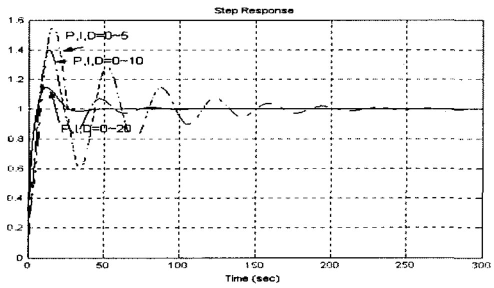

Fig. 24 Response to average values on parameter learning of immune network (P, I, D=5-20).

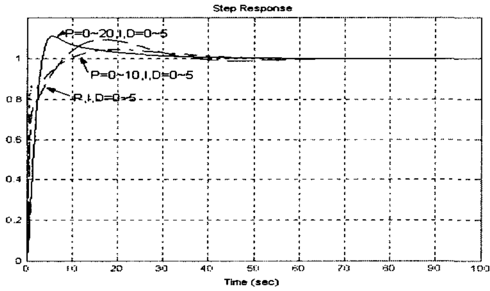

Fig. 25 Response to average values on parameter learning of immune network.

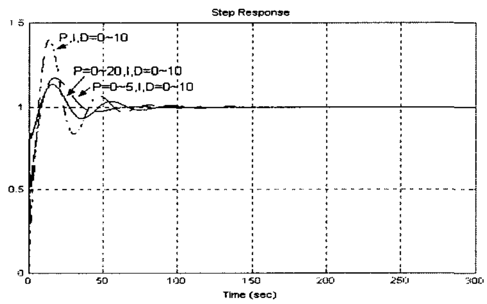

Fig. 26 Response to learning with P=variation and I and D equal to=10.

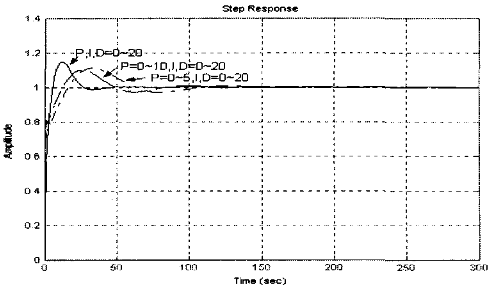

Fig. 27 Response to learning with P=variation and I and D equal to 20.

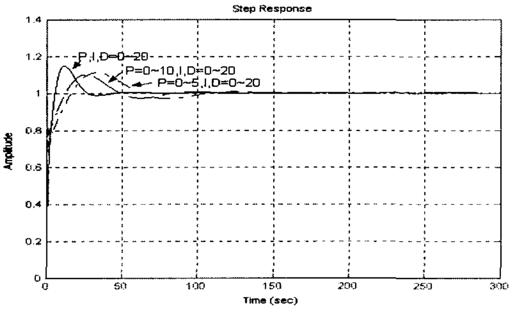

Fig. 28 Response to learning with D=variation and P and I equal to 10.

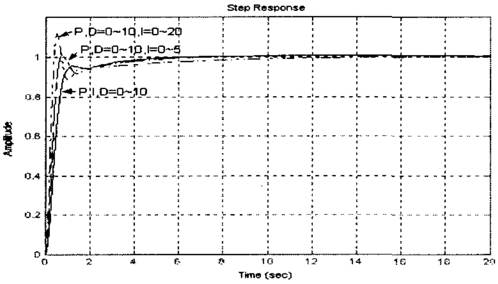

Fig. 29 Response to learning with D=variation and P and I equal to 10.

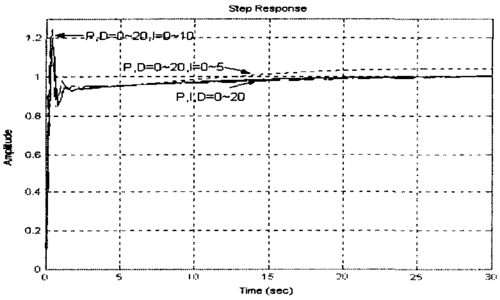

Fig. 30 Response to learning with D=variation and P and I equal to 10.

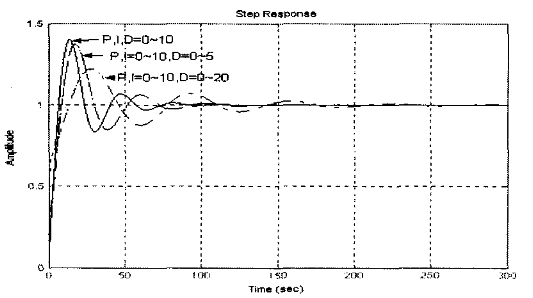

Fig. 31 Response to learning with D=variation and P and I equal to 20.

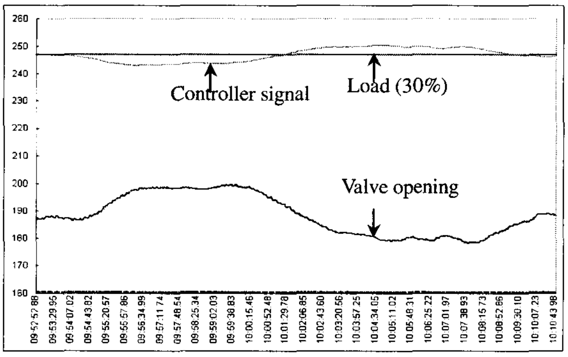

Fig. 32 Load simulation using operating data.

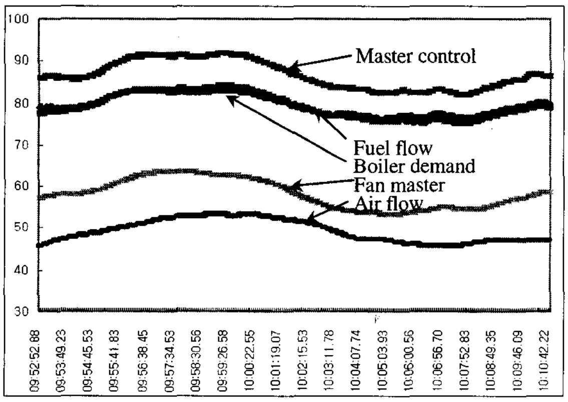

Fig. 33 Simulation result in steam control loop by the conventional PID controller.

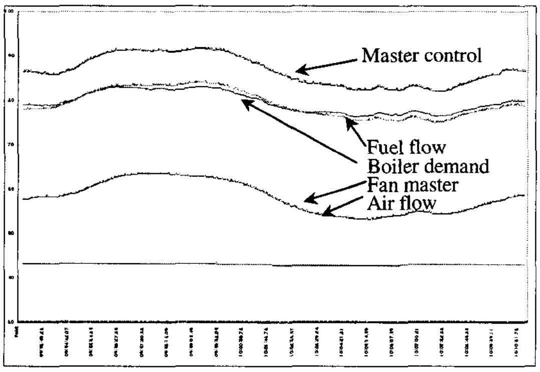

Fig. 34 Simulation result in steam control loop by the 2-DOF PID Controller.

5.6 Simulation Using Operating Data of Power Plant

Fig. 32 shows the result of load simulation using operating data of the Boryong power plant. That is, the data achieved during operating (load level: 30%) is applied to the controller designed in this paper. Fig. 32 illustrates the controller signal and boiler demand. Fig. 33 represents the result of the steam temperature control loop with the conventional PID controller. On the other hand, Fig. 34 shows the result of simulation in the same loop with the 2 - DOF PID controller. The responses are similar.

Therefore, the designed 2-DOF PID controller can effectively be used in the control loop of a power plant using a simple control loop without a feedforward and feedback cascade loop.

6. Conclusions

Up to now, the PID controller has been used to operate the power plants. However, achieving an optimal PID gain is very difficult for the steam temperature control loop with disturbances and without any control experience since the gain of the PID controller has to be tuned manually by trial and error the design of the PID controller may not cover a plant with complex dynamics, such as large dead time, inverse response, and a highly nonlinear characteristic.

To design an optimal controller that can actually be operated on a generating system in Seoul, Korea, this paper focuses on comparing the characteristics of the PID controller and the modified 2 - DOF PID controller for developing tuning technology on the DCS. The modified 2 - DOF PID controller is designed by rearranging the 2 - degrees parameter to enable parameters of controller to fit into the power plant when it has a disturbance.

Of course, there are many kinds of advanced control theories and controllers. However, all theoretical controllers should be proven on the physical plant or equipment before they are operated on the real plant for safety and reliability.

For this purpose, we acquired transfer function and operating data from the start-run-stop procedure of the power plant and compared the characteristic of the controllers designed using this transfer function and the operating data.

Also, we suggest an immune network tuning method of the PID controller. Parameters P, I and D encoded in antibody are randomly allocated during selection processes to obtain an optimal gain for plant. The object function can be minimized by gain selection for control, and the variety gain is obtained as shown in Table 1. Through this table, an optimal gain required in the plant characteristic can be acquired. All results of simulation represent more satisfactory response than tuning in the Zielger Nichols method. The parameter obtained by the immune system learning depends on the initial range of the parameter. Application of the immune system to steam temperature in the power plant control system is alternated to implement optimal gain of the complicated control loop. The suggested controller can also be used effectively in the power plant since the controller needs no feedforward or cascade loop. Experiments and more detailed discussion of the PID parameter and the immune network tuning rules should be performed in future studies.

Table 3-a Variation of range P, I, D

Item	P=0-5 I=5 D=5	P=0-10 I=5 D=5	P=0-20 I=5 D=5	P=0-5 I=10 D=10	P=10 I=10 D=10	P=20 I=10 D=10
Object value	33.9605	23.9675	32.0953	27.5662	17.1856	11.5160
P	2.1904	3.2942	3.2635	2.199	8.2801	11.5983
I	4.2604	4.9477	4.9977	9.8844	9.8954	9.8955
D	4.3980	4.6729	0.5497	7.4212	1.6318	4.3980

Table 3-b. Variation of range P, I, D

Item	P=5 I=20 D=20	P=10 I=20 D=20	P=20 I=20 D=20	P=5 I=0-5 D=5	P=5 I=0-10 D=5	P=5 I=0-20 D=5
object value	18.0364	13.4347	10.8453	33.9606	26.7613	27.0412
P	2.6457	9.7672	5.3462	2.1904	3.1975	2.1990
I	15.3932	14.5662	19.7008	4.2604	1.2004	17.3172
D	15.3930	3.0214	9.7634	4.3980	4.8249	4.9993

Table 3-c Variation of range P, I, D

Item	P=10 I=0-5 D=10	P=10 I=0-10 D=10	P=10 I=0-20 D=10	P=20 I=0-5 D=20	P=20 I=0-10 D=20	P=20 I=0-20 D=20
object value	16.1983	17.1856	11.1638	19.1644	13.6286	10.8453
P	9.6207	8.2801	9.3447	3.279	3.8328	5.34623
I	4.6729	9.8954	14.2313	1.7890	9.7831	19.7008
D	2.3343	1.6318	4.3902	16.8700	19.6516	9.7634

Acknowledgements

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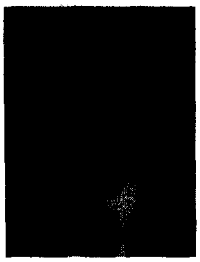

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