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A Fuzzy Controller for the Steam Generator Water Level Control and Its Practical Self-Tuning Based on Performance

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증기발생기 수위제어를 위한 퍼지제어기 구현 및 제어성능지수를 이용한 제어기의 Self-Tuning

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Abstract

The water level control system of the steam generator in a pressurized water reactor and its control problems are analysed. In this work a stable control strategy particularly during low power operation based on the fuzzy control method is studied. The control strategy employs substitutional information using the bypass valve opening instead of incorrectly measured signal at the low flow rate as the fuzzy variable of the flow rate during low power operation, and includes the flexible scale adjusting method for fast response at a large transient. A self-tuning algorithm based on the control performance and the descent method is also suggested for tuning the membership function scale. It gives a practical way to tune the controller under real operation. Simulation was carried out on the Compact Nuclear Simulator set up at Korea Atomic Energy Research Institute and its results showed the good performance of the controller and effectiveness of its tuning.

요 약

증기발생기의 수위제어시스템에 대해 특히 저출력시 수위제어의 문제점을 분석고찰하고 퍼지제어기법을 기반으로 한 안정되고도 신속한 수위제어에 관한 연구가 주로 수행되었다. 문제해결의 한 방안으로서, 중요 제어변수임에도 불구하고 저출력운전시 저유량구간의 측정불량으로 인해 사용할 수 없는 유량신호를 대신하여 밸브개도를 이용한 대체정보를 채용하였으며 또한 소속함수크기의 유동적인 조정방법을 이용하여 수위오차가 크게 발생한 과도상태시에는 신속한 수위회복이 이루어지도록 하였다. 실제운

전환경에서 제시된 제어기를 튜닝하기 위한 방법으로서 제어성능지수 및 decent method를 이용한 소속함수의 self-tuning 기법을 제시하였다. 원자력연구소의 연수원에 설치된 교육훈련용 시뮬레이터에서 수행된 실험결과는 제시된 제어기 및 튜닝방법의 안정되고 우수한 성능구현 및 실질적인 유용성을 보여주고 있다.

1. Introduction

When the steam generator of the nuclear power plant is operated at low power, the water level is very perturbed, which has been a major factor causing reactor trip during the start-up operation. The operating setpoint of water level is 50% of the narrow range measurement span. In Kori power plant(Westinghouse type) the reactor is supposed to be tripped to prevent its overheat due to lack of the heat removal capacity when the water level is lower than 17%. This occurs frequently during low power operation. In this paper a stable control method using fuzzy logic was studied based on the problem analysis particularly during low power. Manual operation at the control panel of the simulator was also practiced in order to understand the operator's control rules. Emphasis of this study is placed on simplicity for the ease of application at the real plant environment and on flexibility for rapid and stable response during large transient.

2. Analysis of the Water Level Control System and the Low Power Operation Problems

There are some problems causing troubles in the water level control at low power. The first one is the very low temperature of feedwater compared to that of the primary coolant or the water in the steam generator, which causes large time delay in the control response and also the nonminimum system characteristic. This is because steam with which the feedwater is heated up is not provided from turbine until synchronization. The second one is the continuous swing of pressure due to the steam dump process before synchronization, which causes swelling and shrinking of water inventory in the steam generator and hence continuous level perturbation. Most importantly, the third one is the incorrectly measured steam flow rate at low power and the flow error as a major control variable is not available. The flow error is an important factor to prediction of water level change in the time following and it is critical for the stable control of water level with large time delay and disturbance. By this reason the existing PI controller refers only to the level error during low power operation and it does not produce the correct control action at that time. Therefore, handling this problem may be a key to the stable water level control.

The approximate dynamics of the water level over the feedwater flow rate is shown in (1). This relation was obtained experimentally from Uljin nuclear plant

$$G_p(s) \fallingdotseq \frac{0.1977s^2 - 0.0292s + 0.001}{s^4 + 0.6121s^3 + 0.0581s^2 + 0.001s} \tag{1}$$

Given PI controller as follows

$$G_c(s) = K\,(\,1 + 1\,/\,\tau s\,) \tag{2}$$

then the closed-loop transfer function of the control system is

$$H(s) = \frac{G_c(s) \cdot G_p(s)}{1 + G_c(s) \cdot G_p(s)} \tag{3}$$

Figure 1 presents the root locus of H(s) for $K=0$ to ∞ and $\tau=500\text{sec}$. It shows that the root is located at the right side except for extremely small K. Figure 2 presents the step responses of H(s) for two cases of the time constant τ when gain K is 0.02. It is noted that very large value of time constant is required for better stability. Figure 3 presents the step responses of H(s) for two cases of the control gain K when time constant τ is 500sec. It is shown that even very small increase of gain makes the system divergent. From this observation the given PI controller is not proper for the stable control during transients.

Several efforts to improve the water level control system have been made. But most of those attempts based on mathematical model have failed to apply to the real system. It is because the control object is characterized by large nonlinearity and very high order system model, and its reduced form for control system is not available. So the water level control at low power is still relied on the experienced operator's manual control.

3. Water Level Control Using the Fuzzy Logic

In this case the control method using fuzzy logic algorithm is a good approach because it has the advantage of the nonlinearity control capability and the manual control rules suffice for the fuzzy logic control algorithm. However, although several papers using the fuzzy logic algorithm have been presented, they do not give any proper suggestion for the stable control at low power operation because the measured signal of flow rates is not available. [2] suggested a very simple rule set but the incorrect measurement was not considered at low power in it. [3] and [4] employed excessively complex control rules to avoid the trouble in incorrect measurements.

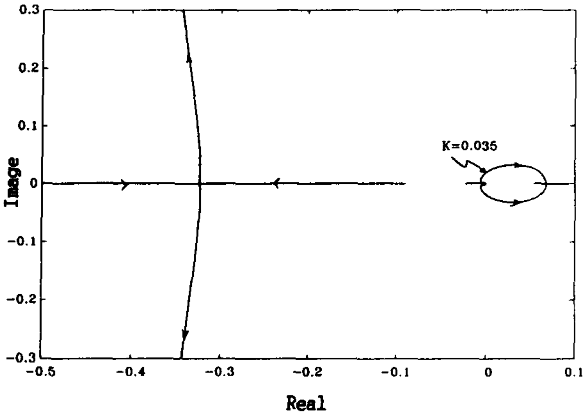

Fig. 1. The Root Locus of H(s) for K=0 to ∞ at τ=500sec

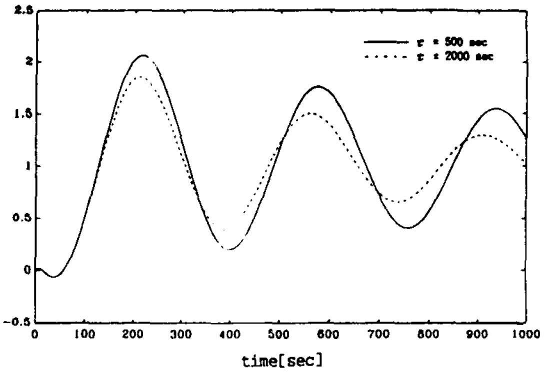

Fig. 2. The Step Responses of H(s) for τ=500sec and τ=2000sec

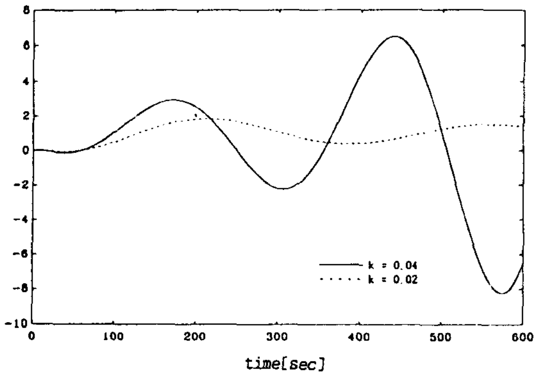

Fig. 3. The Step Responses of H(s) for K=0.04 and K=0.02

3.1. Rule Establishment and Substitutional Fuzzy Variable

It is not always easy to extract the most reasonable representations for rules from human knowledge. With well-selected control variables and rules, the controller would be tuned more easily in the real environment. A more clearly describable relationship between the input and output could also be helpful for the effective adjustment in tuning process. More simple rule establishment is necessary for this purpose[3, 4].

The control rules applied here were established based on operators' knowledge and our own manual control experience on the simulator control panel. They are composed of the combinations of the level error and the flow error. That is, the feedwater valve opening amount is determined referring to these two variables. For example, if the water level is lower than its setpoint and the steam flow rate is smaller than the feedwater flow rate, no control action is taken, i. e. the valve keeps its previous position. Then the water level will increase over the next sampling period because the inflow water is more than the outflow water.

A rule is expressed as follows:

IF LE is A and FE is B, THEN ΔU is C.

where

LE: Level Error = setpoint − measured level

FE: Flow Error = steam flow rate − feedwater flow rate[kg/sec]

ΔU: valve control percentage

The control rules are shown in Table 1 and the membership functions for the control variables, in Figure 4.

Table 1. Control Rules

LE FE	PB	PS	ZO	NS	NB
PB	PB	PB	PM	PS	ZO
PS	PB	PM	PS	ZO	NS
ZO	PM	PS	ZO	NS	NM
NS	PS	ZO	NS	NM	NB
NB	ZO	NS	NM	NB	NB

By the way, when the same control rule in Table 1 is applied over all power range we face a trouble with unavaliable flow error at low power as mentioned previously. Less experienced operator also has difficulty in manual control at that time. To solve this problem a method to employ a substitutional information for invalid signal of the flow error during low power is proposed in this study. This information can be induced from the feedwater valve position considering some process conditions.

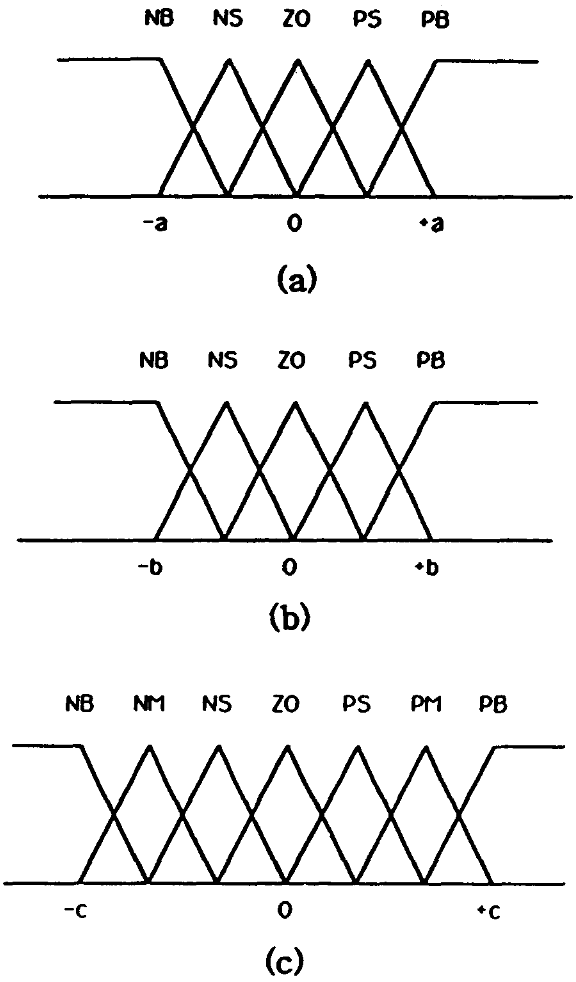

Fig. 4. Membership Functions of (a) Level Error(LE), (b) Flow Error(FE), and (c) Valve Control(ΔU)

The generated steam flow, Qv, within the steam flow is proportional to reactor power rate, q, at a given pressure condition.

$$Q_V \propto q \qquad (4)$$

Feedwater flow rate is approximately linear to feedwater valve position except the dead band area of valve operation. So it can be described as a function of valve position, h, as follows.

$$Q_C \fallingdotseq a_1 \cdot h + a_0 \qquad (5)$$

Under condition of constant reactor power and water level, the generated steam flow, Q_v, is equal to feedwater flow, Q_c. At that time the required valve position, h_s, to maintain the water level at a reactor power can be described approximately as follows.

$$h_S \fallingdotseq \beta_1 \cdot q + \beta_0 \qquad (6)$$

where q is the reactor power and β_i's are coefficients. It can be used as a reference for steam flow.

Let h_m denote currently measured valve position. In case of $h_s > h_m$ steam flow rate is expected to be more than feedwater flow rate and then flow error is positive. In case of $h_s < h_m$, steam flow rate is expected to be less than feedwater flow rate and then flow error is negative. Therefore, the difference between these two values in (7) can be used for substitutional fuzzy variable of flow error during low power.

$$FE_L = h_S - h_m \qquad (7)$$

Although there exist somewhat uncertainties or nonlinearity in the process of introducing the valve reference for steam flow, h_s, they are negligible and can be handled without any trouble by using fuzzy concept. Coefficients β_i's in (6) can be estimated easily by using operation data rather than using mathematically complex relations.

For fuzzy variable of the flow error the controller takes the estimation signal in (7) until the synchronization and the measured signal thereafter.

3.2. Membership Function Scale and its Flexible Adjustment

Physical system limitations and operational constraints should be considered in tuning of the membership function scale. Membership function scale of the valve control variable is bounded by both of the valve stroke time and the sampling period, and that of level error, by the stable operation range of water level. Their scales applied in this simulation study are 5% level and 0.1% opening.

Now the variable to tune is flow error. According to the control strategy mentioned above, it takes two scales, one for the estimated signal during low power range and the other for the measured signal during higher power range. Because the flow error has effects on the water inventory and hence causes the level to change in the time following, the maximum flow error is limited by its membership function scale with the previously established rules. Its large value may make the system divergent. By the way, when a transient with the large level error beyond normal operation range occurs, large flow error should be allowed in order to recover rapidly to the setpoint level. It is realized by adjusting its membership function scale for the large level error.

The flexible adjusting effect of the flow error can be explained with the different fuzzification depending on the membership function scale and the rule transfer between the applied rules. The membership functions of flow error for two different scales are depicted as in Figure 5. Upper one is for the level error within normal operation range and lower one, for the large level error beyond normal operation range. Assume that LE is PB and the measured flow error is x.

In upper case, the dominating fuzzy number of

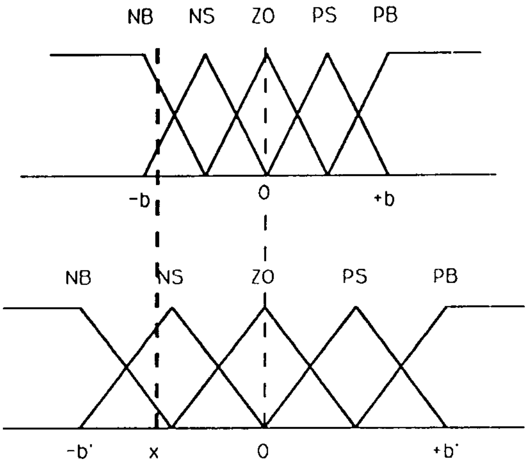

Fig. 5. The Membership Functions of Flow Error for Different Scales

flow error is NB and then the dominating control rule is

IF LE is PB and FE is NB, THEN ΔU is ZO.

In lower case, the dominating fuzzy number of flow error is NS and then the dominating control rule is

IF LE is PB and FE is NS, THEN ΔU is PS.

This means that more flow error is allowed in lower case than in upper case and the water level is recovered rapidly to its setpoint for the large transient and is kept stable within the normal range.

The turbine power was also considered in adjusting the membership function scale of flow error because the feedwater temperature depends on it after syncronization and the temperature affects the delay time of contol response. Therefore, the membership function scale of flow error, b, is adjusted by both of the level error and the turbin power. If the level error is larger than ±0.5%, b would become larger according to the level error but its increase amount would be decided by the turbine power.

3.3. The Self-tuning of the Membership Function of Flow Error

In respect of automation and application to the nuclear power plant a systematic and reasonable tuning method is required for safe operation during tuning process. The varied papers have discussed this subject based on the different ways, neural network, genetic algorithm, or others. As a practical way to tune a membership function scale at a complex system a self-tuning method based on control performance measures and gradient descent method is suggested here. [5] suggested a real-time tuning method based on the measure function of error and the rule estimation at the steam generator water level controller. It provides a fast tuning method but the reference tuning index and the initial segmentation of response region are hard to decide properly.

The fundamental idea of the suggested method in this paper is from [6] and [7]. In [6] the membership function scales are tuned using performance evaluation and inferences. That is,

IF performance measure is X, THEN Δs is Y

where performance measure is overshoot, rising time, or oscillation of control response and s is the change of membership function scale.

In this method additional reasoning and tuning process is required and this method is effective when control performance of the system is well known. On the other hand in [7] the membership function is tuned by minimizing the difference between the measured output and the reference. That is, the membership function parameters are tuned using descent method as follows.

$$a_{ij}(t+1) = a_{ij}(t) + K \frac{\partial E}{\partial a_{ij}} \tag{8}$$

where E is the error between the desirable output and the measured output, and a_{ij} is width or center of membership function. In this method, however, output reference should be known and a lot of iterations are required.

Now another approach is attempted with combination of the above methods. Both of maximum overshoot and rising time are desirable to be small for good performance of the system. However, no controller can satisfy both of them at the same time because there exists trade-off between these two parameters. The performance measure function is defined as follows,

$$M = K_1 \times OV + K_2 \times Tr \tag{9}$$

where OV is maximum overshoot and Tr, rising time. K_1 and K_2 are weighting factors to decide which performance is more significant. With larger K_1 the emphasis is placed on getting the smaller overshoot and with larger K_2, on getting the shorter rising time.

Minimum value of M in (9) can be considered as a compromising point for performance parameters so that controller parameters would be tuned to that point. Figure 6 presents the performance measures versus damping ratio for the second order system. Sum of two parameters, $y1 + y2$ is a performance

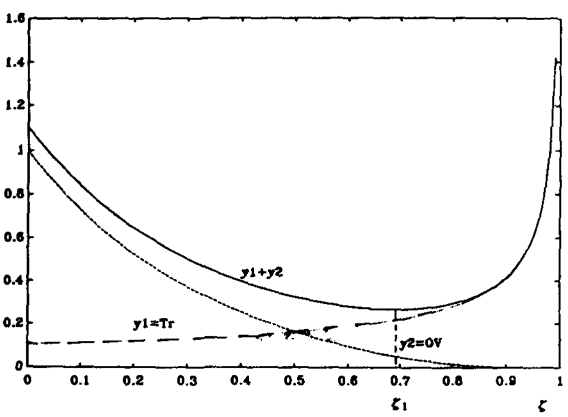

Fig. 6. The Performance Measures of the Second Order System

measure function and is minimized at ζ_1.

As mentioned previously, flow error is associated with change rate of steam generator inventory during the time following and its membership function scale affects control response. It acts like the reversed damping factor in the control process. Figure 7 presents the performance measure function versus the membership function scale of flow error, b, conceptually. For the large value of b, control response has small rising time and large overshoot with more instability, and for the small value of b, large rising time and small overshoot with too slow response.

The membership function scale of flow error, b, can be tuned to b_{opt} at the minimum value of performance measure function, M_1 from any arbitrary point on the curve of M by descent method as follows.

$$b(n+1) = b(n) - H \times \frac{\Delta M}{\Delta b} \tag{10}$$

where $\Delta M = M(n) - M(n-1)$,

$\Delta b = b(n) - b(n-1)$,

H : modification rate,

n : step response iteration.

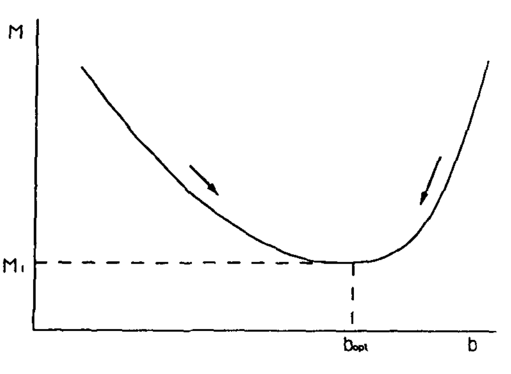

Fig. 7. Performance Measure Function Versus Membership Function Scale

b may be tuned flexibly through all power rates considering different time delays over power rate. A way to do this is the interpolation of data on a few points of power rate. The tuning experiment in this simulation study was done only for full power.

4. Simulation and Conclusion

The Compact Nuclear Simulator(CNS) set up at Korea Atomic Energy Research Institute was used for the simulation of the methods suggested here as well as operation experience through the manual control practices. It simulates Kori nuclear unit 3&4 (1000MWe each) in Korea, and its reactor dynamics is simulated by SMABRE code.

β_1 and β_0 in (6) were estimated using data acquired during reactor power-up operation at CNS. Applying line fitting method by least squares approach for 14 points, $\beta_1 = 2.3658$ and $\beta_0 = 0.2326$.

The simulations were performed in three ways. The first one was carried out under condition of 2% to 14% power-up operation in order to compare the existing PI controller with the suggested fuzzy logic controller. Figures 8 and 9 present the water level response of the existing PI controller and flow rates of feedwater and steam at that time. Figures 10 and 11 present the water level response of the suggested fuzzy logic controller and the flow rates at that time. After initial perturbation the existing controller took more than 33 minutes to recover the water level to its setpoint, and the suggested controller took about 18 minutes. The suggested controller is proved to have much better performance than the existing controller.

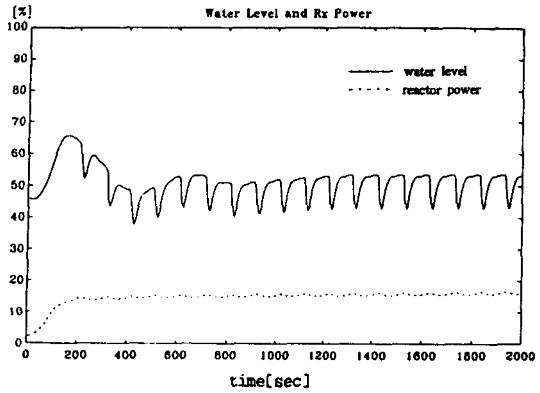

Fig. 8. The Water Level Response of Existing PI Controller

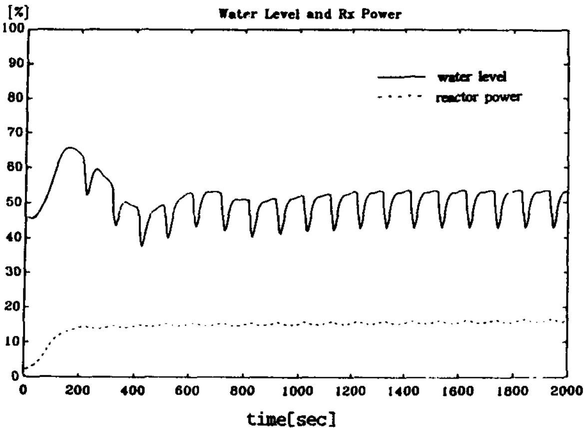

Fig. 10. The Water Level Response of Suggested Fuzzy Logic Controller

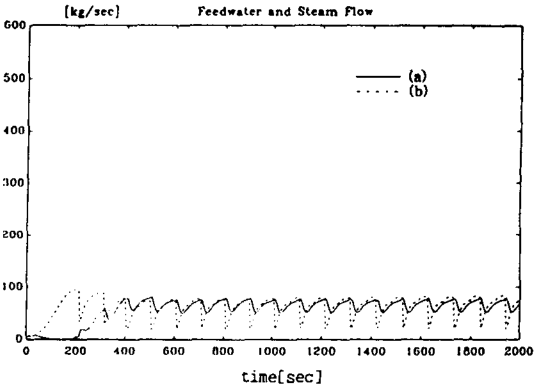

Fig. 9. Flow Rates of (a) Feedwater and (b) Steam at PI Control

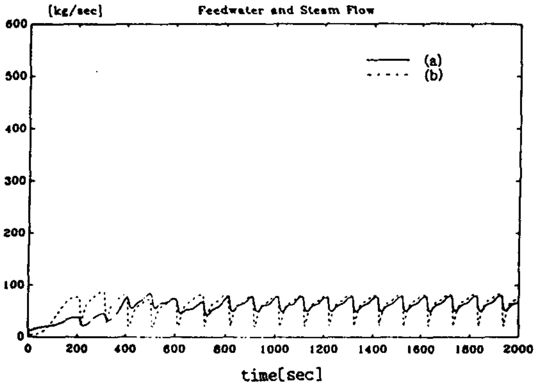

Fig. 11. Flow Rates of (a) Feedwater and (b) Steam at Fuzzy Logic Control

The second simulation was carried out in order to see the effect of the flexible scaling of membership function under condition of the level setpoint change from 50% level to 60% level during 100% power operation. Figure 12 presents the step responses for the fixed scale and the flexible scale and Figure 13 presents feedwater flow rates at that time. It shows that the rising time is shorter in flexible case than in fixed case and the control action has been finished earlier in case of flexible adjusting.

The third simulation was carried out for the suggested self-tuning method with two cases of weighting factors. Each performance measure function M was obtained with the step reponses under condition of level setpoint change like the second simulation. The results are shown in Table 2 and 3. Weighting factors in Table 3 were decided so that overshoot might be more significant than rising time compared with those in Table 2. From Table 2 the performance measure function is of the minimum value at 15th iteration and the membership function scale of flow error, b, is expected to be tuned to around 25 [kg/s] when overshoot is 0.39989% and rising time is 1.84 min. From Table 3 the performance measure func-

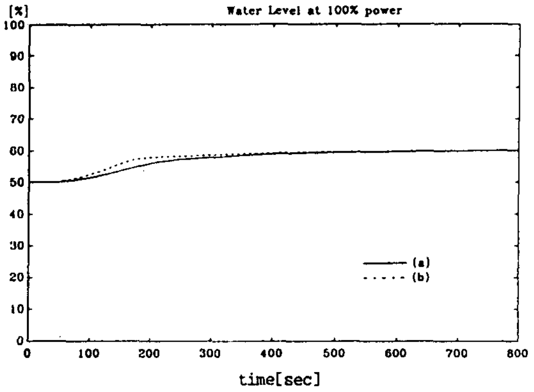

Fig. 12. The step responses of water Level for (a) Fixed Scale and (b) flexible Scale

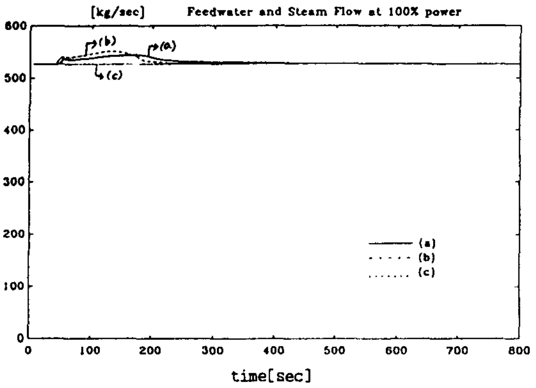

Fig. 13. Feedwater Flow Rates for (a) Fixed Scale and (b) Flexible Scale, and (c) Steam flow Rate

tion is of the minimum value at 19th iteration and b is expected to be tuned to around 22 (kg/s) when overshoot is 0.06098% and rising time is 2.18 min. It is tuned to get shorter rising time and larger overshoot with $K_1=1$ and $K_2=1$ than with $K_1=5$ and $K_2=1$. By setting the weighting factors differently the membership function can be tuned to the direction in which the emphasized control performance is acquired in controller tuning.

This study has presented that through the application of fuzzy logic algorithm, the control system for mathematically high order(or unknown) system can be implemented more easily with good performance

Table 2. Tuning Result for $K_1=1$ and $K_2=1$

n	OV(%)	Tr(min)	b(kg/s)
1	0.00280	7.69333	7.20000
2	0.01210	5.29333	10.26250
3	0.23377	4.17667	14.14498
4	0.13828	3.95667	15.29759
5	0.31316	3.67667	16.66616
6	0.39619	3.59000	17.05021
7	0.03272	3.57333	17.09757
8	29.18661	1.20000	57.23222
9	28.52815	1.24333	53.89588
10	27.64410	1.25000	52.97403
11	23.56744	1.29000	48.21517
12	19.11163	1.32000	43.97396
13	11.07639	1.40667	38.75634
14	2.85500	1.66000	31.13930
15*	0.39989	1.84000	25.90888
16	0.50718	2.12667	23.73399
17	0.60940	2.04000	24.63968
18	0.61250	2.05000	24.55381
19	0.65404	2.00667	25.31651
20	0.47690	1.92000	25.32824

Table 3. Tuning Result for $K_1=5$ and $K_2=1$

n	OV(%)	Tr(min)	b(kg/s)
1	0.00280	7.69333	7.20000
2	0.02301	5.25333	10.36225
3	0.22107	4.19333	14.06052
4	0.22560	4.17333	14.15471
5	0.21613	4.20000	14.01405
6	0.13822	4.14000	13.27755
7	0.02438	5.72333	10.22584
8	0.04011	4.96667	11.88738
9	0.08357	4.32333	13.92762
10	0.14746	4.07000	14.97180
11	0.14114	4.15333	14.65505
12	0.17589	3.95667	15.47183
13	0.04554	3.58333	15.61213
14	25.80905	1.23000	52.14524
15	8.10248	1.51333	34.83707
16	0.04065	5.90333	9.34346
17	0.00042	23.49667	2.29873
18	0.08303	4.09333	14.64282
19*	0.06098	2.18667	22.33487
20	0.41097	2.11333	23.64592

and possible uncertainties in the design process can also be handled with less effort. This study also suggested that substitutional information using valve position be employed for unavailable fuzzy control variable of flow error through understanding of process and fuzzy concept. The tuning method suggested here would be of practical use for the real plant with its viewable path and available on-line tuning.

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