Control and Cybernetics

vol. **27** (1998) No. 4

A fuzzy controller with a real-time tuning algorithm and its application to a steam generator water level control

by

Chul-Hwan Jung, Kee-Choon Kwon

MMIS Team,
Korea Atomic Energy Research Institute,
P.O. Box 105, Yusong, Taejon, 305-600, Korea

Abstract: It is nesessary to tune the fuzzy rules and the scaling factors in real-time control of a large scale system, the steam generator of a nuclear power plant, as it is related to safety and availability of the plant. A novel real-time tuning algorithm of fuzzy controller based on the scaling factors is proposed and applied to the steam generator water level control system of the nuclear power plant. The new real-time tuning algorithm adopts a variable reference tuning index for a good system tuning response and an instantaneous system fuzzy performance for scaling factor tuning. For the fuzzy steam generator controller, an image signal of feedwater flow error at low power is proposed and pressure compensation rules and a gain scheduler of feedwater temperature are designed also. The fuzzy controller of the steam generator water level is simulated by the proposed method. The simulation results show that the improved performance of the steam generator water level controller by the proposed method.

Keywords: fuzzy controller, instantaneous system performance, self-tuning, scaling factor, steam generator

1. Introduction

Since the work of Zadeh, fuzzy logic controller is one of the most active research areas in the control enginnering. Fuzzy logic control methodologies have had many improvements and it's application papers are presented Bare, Mulholland and Sofer (1990), Ramaswamy, Edwards and Lee (1993), Ruan, D'hondt, Govaerts and Kerre (1994). The reason for that is a fuzzy logic controller employs the control rules of conditional linguistic statements on the relationship of the system variables and has the advantages of emulating the behavior of a human operator and of dealing with model uncertainty. There are some studies of fuzzy control theory in the nuclear power plant control Ramaswamy, Edwards and Lee (1993), Han and Lee (1994), Kuan, Lin and Hsu (1992), Ikonomopoulos and Tsoukalas (1993), Akin and Altin (1991), Tanji, Kinoshita, Fukuzaki and Kobayashi (1993), and the steam generator water level controller using fuzzy logic was actually installed at the Fugen nuclear power plant Ruan, D'hondt, Govaerts and Kerre (1994).

The fuzzy controller is designed by human experiences and control rules which are usually subjective. Therefore, the rules are different as they are made by different experts. It is difficult to acquire good control performance for the system from which there has been little experience. Therefore, it is necessary to tune the rules and the scaling factors for good performance after the design of the control rules. As the tuning of the controller is a laborious work and time consuming efforts, the self-tuning methods of fuzzy controller has been developed Bare, Mulholland and Sofer (1990), Maeda and Murakami (1992). When the controller is designed, it is tuned to the circumstances of system simulation. Even if the controller is tuned well, tuning of the rules or scaling factors are needed after the installation of the controller at a real plant because of model mismatch and other filed factors. Also the controller may need to be retuned because of system obsolescence and changes in circumstances involving the controller.

The steam generator converts heat to steam for the production of electricity and it is an important component especially for safety related requirements of the nuclear power plant, and it is also a large system which is related with availability of plant. One must avoid repeated tuning processes and long tuning times for this large system to reduce the probability of accident and undesirable influences on the total system. Therefore, a tuning method which has a good tuning performance is needed for a large system which is directly related to the total system.

There are on-line tuning methods of the fuzzy controller, but there are a few real-time scaling factor tuning methods. To get good control performance, we tune the rules or input/output scaling factors. The tuning part may be a reference model, a parameter adjuster or a reference response to compare between process output and setpoint for the tuning of rules. There are several methods to tune the rules or control gains by complicated computing processes Aldridge (1992), Palm (1993), Katayama, R., Kajitani, Y. and Nishida, Y. (1992), and these methods can tune the rules after calculation of control performance index such as rising time, amplitude, overshoot or settling time, Maeda and Murakami (1992), Daugherity, Rathakrishnan and Yen (1992). So these tuning methods can tune the controller by on-line but not real-time.

In this paper, a novel real-time scaling factors tuning method is proposed and applied to the steam generator water level control system of the nuclear power plant.

2. Real-time scaling factors tuning

2.1. Scaling factors tuning

Scaling factors map input/output value to the fuzzy variable domain. The change of input scaling factors connects input values to suitable rules, and the change of output scaling factors can adjust the amplitude of control output. For example, Fig. 1 shows the relationship between the scaling factors and the gain characteristic of the controller for the control error e. In Fig. 1, when scaling factor d of Δu is constant, the controller gain seemingly increases by decreasing the scaling factor a of e. Even when the scaling factor a is fixed, the same effect is obtained by changing the scaling factor d. However, if the gain function are nonlinear functions, the results of the gain adjustment by these methods are not completely the same. But in this way the change of the scaling factors gives elasticity to the characteristics of the controller without changing the tendency of the characteristics. Generally, the modification of control rules change the characteristics of the gain functions; the adjustment of the scaling factors determines the tilt of gain characteristics, so we know the adjustment of a scaling factor is important in tuning the controller.

Maeda and Murakami (1992) made scale adjustment rules and defined a fuzzy performance function for scaling factors tuning by evaluating the control results. The elements of the evaluation were overshoot, reaching time and amplitude. These evaluation values were given at the end of the control interval. The scaling factors were adjusted using final fuzzy performance at the end of the control interval, so this method cannot tune the scaling factors with real-time, that is to say, the scaling factor can not be tuned at every sampling time.

Bare, Mulholland and Sofer (1990) defined a tuning index as follows:

$$\rho = \frac{e_{n+1}}{e_n} \tag{1}$$

where e_{n+1} and e_n are two consecutive errors defined as the difference between process output and setpoint value at step n and $n+1$. Here, the heuristic tuning approach was used as the following; if ρ is greater than a given value C, then the scaling factor for error is changed to move the pointer in or out by one discrete element in the universe of discourse, where the pointer is used to indicate the quantization result of error in the fuzzy controller. For example, if the new data indicate overshoot outside the prescribed error ratio, the pointer would be moved one increment to left to 'slow down' response. The value of the reference tuning index is arbitrarily constant, so the response of the system could be overshoot or undershoot according to the constant reference value and could require long tuning times. If the response of the system approaches the setpoint at a slow rate, it has the oscillations phenomenon of system response because the reference tuning index is constant from large error to small error. This method is not effective for the state variation of a system because it uses a constant increase or decrease in the quantity of scaling factors.

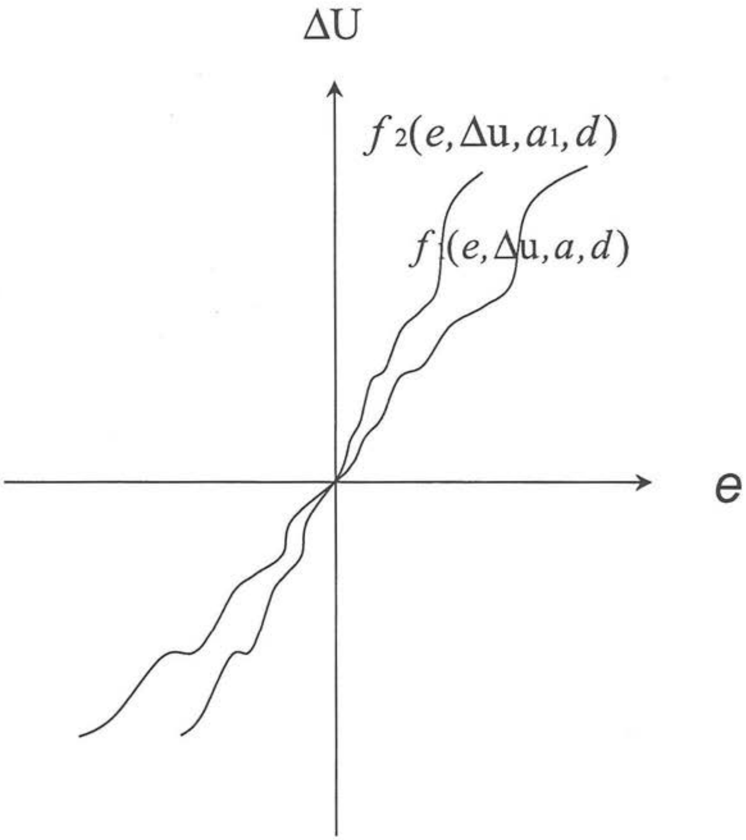


Figure 1. A gain function for error e and change of manipulated value $\triangle u$.

2.2. Variable reference tuning index

As reviewed previously, the system performance index is calculated by the comparison between the output of a model or a reference response and the output of system at the end of the control interval. The scaling factors are tuned with this system performance index with on-line, but not with real-time. And a neural network or cell mapping is used for controller tuning process Smith, S. (1992). The scaling factor tuning method proposed in this paper uses error ratio as a tuning index and uses a variable reference tuning index according to system response characteristics for advanced tuning performances. The general step response of the system can be divided into response sections, each response section having different slit, so it is unreasonable to use the same constant reference tuning index. Therefore, it is reasonable to use a variable reference tuning index for a good tuning response of a system.

If we divide a system response into two response sections, the variable reference tuning index becoms

$$\rho_{rv} = \begin{cases} \rho_{r1} & 0 \leq |e| < \alpha \\ \rho_{r2} & \alpha \leq |e| < e_0 \end{cases} \tag{2}$$

where ρ_{r1}, ρ_{r2} reference tuning index for a response section, α is constant and e_0 is maximum error at a step input.

If ρ_{r1} equals ρ_{r2} from (2) the reference tuning index is a constant reference tuning index(ρ_{rc}) for error. If we select a ρ_{r2} which has a smaller value than ρ_{rc} for $|e| \geq \alpha$, which means that the rate of error change above α is allowed to be higher than when ρ_{rc} is selected. If we select a ρ_{r1}, a higher value than ρ_{rc} for $|e| < \alpha$, which means that the rate of error change below α is bounded to be slower than when ρ_{rc} is selected. If we divide the response of system into n response sections equally, the ρ_{rv} is

$$\rho_{rv} = \rho_{rk}, \frac{|e_o|}{n}(k-1) \leq |e| < \frac{|e_o|}{n}k \ (k = 1, 2, \ldots, n) \tag{3}$$

where ρ_{rk} is a reference tuning index for response section k and e_0 is the maximum error at a step input. And if we divide the response of system into n response sections arbitrary, the ρ_{rv} is

$$\rho_{rv} = \rho_{rk}, \overline{e_{k-1}} \leq |e| < \overline{e_k} \ (k = 1, 2, \ldots, n) \tag{4}$$

where ρ_{rk} is the reference tuning index for response section k and $\overline{e_k}$ is the maximum error in kth response section.

2.3. Instantaneous system performance

The concept of instantaneous system performance is proposed in order to determine the system performance at the sampling time. We can not use the values of overshoot, reaching time, steady state error and amplitude at the sampling

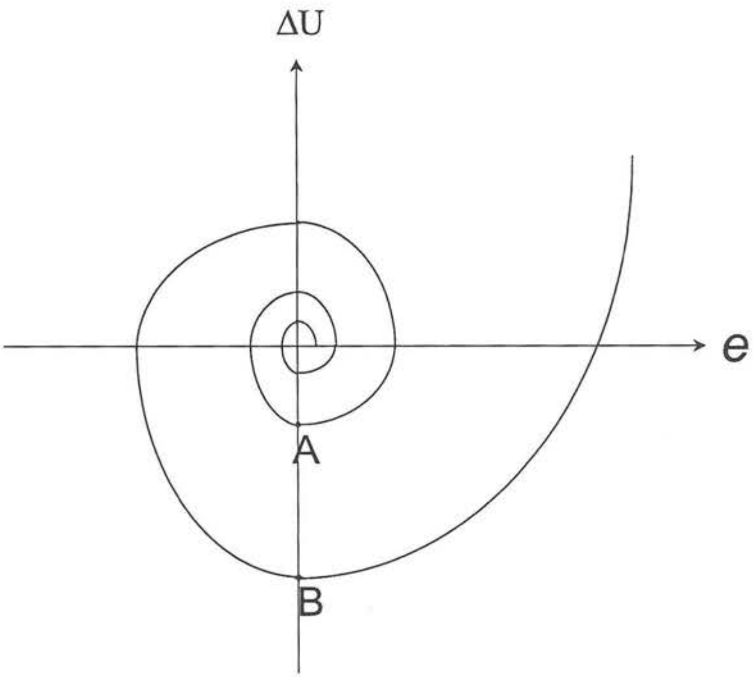


Figure 2. The change of manipulated value $\triangle u$ with error e for step input.

time in the view of real-time base because these values are calculated at the end of the control interval. Fig. 2 shows the relationship of error(e) and change of manipulated value($\triangle u$) for the general response of a step input. From this figure when the value of both error and change of manipulated value have reached zero point, the control value reaches the target value. When the current system state reaches A point or B point, both A and B points have the same error, it is zero. However point B has a lower change of manipulated value than point A. Therefore, the system performance of point B is better than A on the basis of instantaneous system performance, because at point B the control value would be less changed in the future. So the values of error and change of manipulated value are used to determine the grade of instantaneous system performance for scaling factor tuning. The value of error stands for the instantaneous system state and the value of change of manipulated value stands for the instantaneous system state with system information of the future.

Let's define the Instantaneous System Fuzzy Performance($ISFP$) as follows:

$$ISFPe(t) = \mu ISFP_e(e(t)), \tag{5}$$

$$ISFP\triangle u(t) = \mu ISFP_{\triangle u(t)}(\triangle u(t)), \tag{6}$$

Error (or $\triangle u$)	NB	NS	ZO	PS	PB
ISFP	BD	MM	GD	MM	BD

Table 1. ISFP rules

where

NB: Negative Big,
NS: Negative Small,
ZO: Zero,
PB: Positive Big,
PS: Positive Small,
BD: Bad,
MM: Medium,
GD: Good.

where

$$e(t) = S - y(t),$$
$$\triangle u(t) = u(t) - u(t-1),$$

with

$e(t)$: control error,
S : the setpoint,
$y(t)$: the control value,
$u(t)$: the manipulated value,
t : sampling instant.

$ISFPe(t)$ and $ISFP\triangle u(t)$ mean the grade of instantaneous system fuzzy performance for the error(e) and change of manipulated value ($\triangle u$) respectively by the ISFP rules in Table 1. From Table 1, we know that the large values of error and change of manipulated value have a lower grade of instantaneous system fuzzy performance than small values of error and change of manipulated value. The membership functions to measure ISFP are as in Fig. 3.

Define the Instantaneous System Performance (ISP) as follows:

$$ISP(t) = min\{ISFPe(t), ISFP\triangle u(t)\}. \tag{7}$$

By (7), the minimum value between $ISFPe(t)$ and $ISFP\triangle u(t)$ is selected for ISP at t. We can find that if $ISP(t)$ approaches 1, that is to say the system performance at t is of good grade, the values of error and change of manipulated value are close to 0, and if $ISP(t)$ approaches 0, the system performance at t is of bad grade because the one value is big between the error and the change of manipulated value or the values are big for both the error and the change of manipulated value.

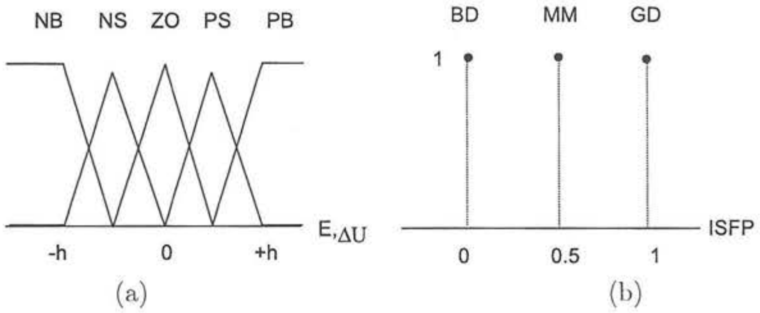


Figure 3. Membership functions for ISFP. (a) Antecedent, (b) consequent.

2.4. The proposed controller

Finally, the scaling factor is tuned in real-time using (8) with (2) and (7).

$$SF(t) = SF(t-1) + W_f(1 - ISP(t))\triangle SF \tag{8}$$

with
$SF(t)$: Scaling factor at t,
$\triangle SF$: Increase or decrease in the quantity of scaling factor,
W_f : Weighting factor.

The (8) means that the final increase or decrease in the quantity of scaling factor is determined according to $ISP(t)$ at sampling time. Therefore, if the instantaneous system performance is good grade, then scaling factor variation is lower than the instantaneous system performance at bad grade. By (8), we can tune the scaling factors effectively according to the instantaneous system performance and we can improve the fuzzy controller in real-time. Fig. 4 shows the proposed real-time self-tuning fuzzy controller.

3. The proposed fuzzy controller for steam generator

3.1. Water level control rules and pressure compensation rules

The control rules for the water level control of the steam generator are based on the operator's control experience Jung, Ham and Lee (1994). The steam generator referred to in this paper is the steam generator of the Kori unit 3 and 4 of pressurizer water reactor, 993 MWe in Korea. The operator controls the steam generator water level by opening and closing the feedwater valve with steam flow rate, feedwater flow rate and steam generator water level. The reference water level is 50% at full power. The water level control rules are in Table 2.

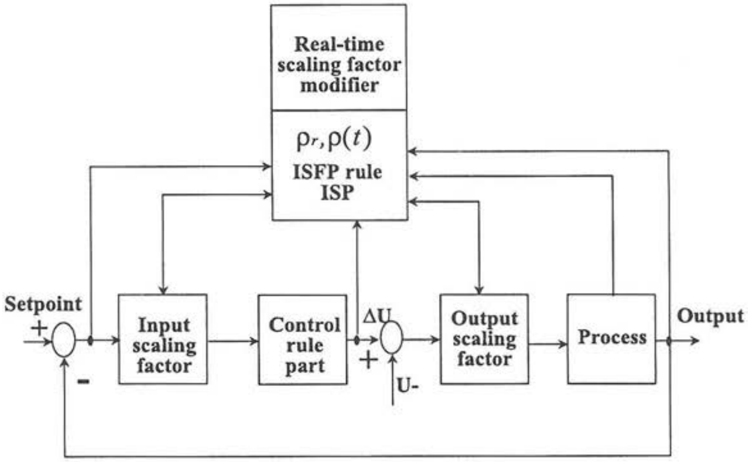


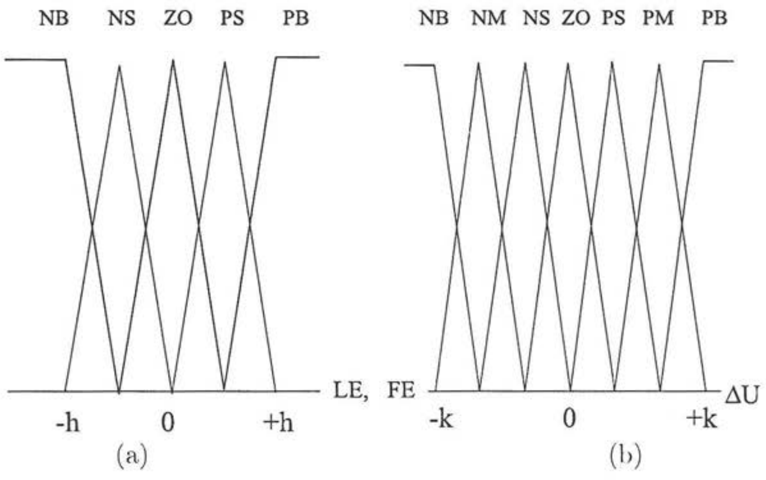
Figure 4. The proposed real-time fuzzy controller.

	FE				
LE	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

Table 2. Steam generator control rules

where

NM: Negative Medium,
NB: Negative Big,
NS: Negative Small,
ZO: Zero,
PB: Positive Big,
PS: Positive Small,
PM: Positive Medium,
FE: Feedwater - Steam flow,
LE: Setpoint - Water level.



(a) (b)

Figure 5. Membership functions for steam generator control rules. (a) Antecedent, (b) consequent.

These control rules use 5 triangle-type membership functions for feedwater flow error and water level error, and use 7 triangle-type membership functions for feedwater valve control as shown in Fig. 5. A center of gravity method is used for defuzzyfication.

The water level of steam generator is varied by the variation of the pressure of the steam generator. It is an element to effect the phenomeon of shrinking and swelling. So the compensation rules for the pressure variation is needed to improve the performance of water level controller. The 25 pressure compensation rules are designed as Table 3. The compensation rules use 5 triangle type membership functions for level error and pressure difference and 5 single tones for pressure compensation as in Fig. 6.

3.2. An image signal of feedwater flow error

The value of feedwater flow rate error is invalid during low power operation. We substitute an image signal for the error of feedwater flow rate. The image signal is introduced in consideration of the relation of process conditions at low power operation. The feedwater valve position can be derived from some operation data as a function of reactor power and can be used as a reference for the steam flow rate at the corresponding power.

$$\theta' \cong \beta_1 W + \theta_0, \tag{9}$$

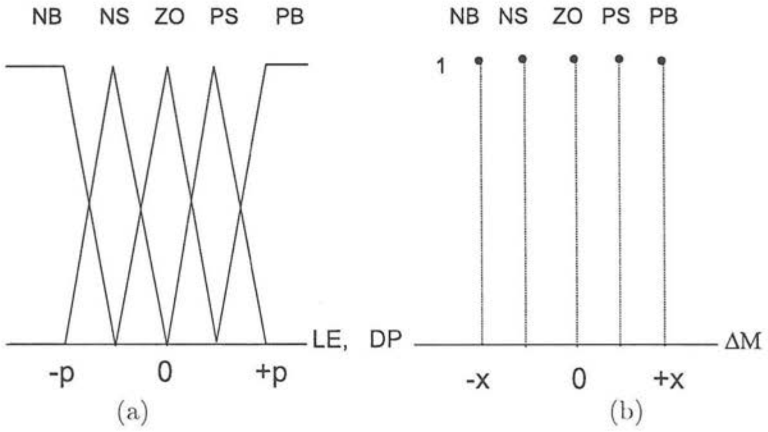
where W is reactor power and β_1 and β_0 are coefficients.

	LE				
NB	PB	PB	PB	PS	ZO
NS	PS	PS	PS	PS	ZO
ZO	ZO	ZO	ZO	ZO	ZO
PS	ZO	NS	NS	NS	NS
NS	PS	ZO	NS	NM	NB
PB	ZO	NS	NB	NB	NB

Table 3. Pressure compensation rules

where

NM: Negative Medium,
NB: Negative Big,
NS: Negative Small,
ZO: Zero,
PB: Positive Big,
PS: Positive Small,
PM: Positive Medium,
PD: $P(t) - P(t - \tau)$,
LE: Setpoint - Water Level.



(a) (b)

Figure 6. Membership functions for pressure compensation rules. (a) Antecedent, (b) consequent.

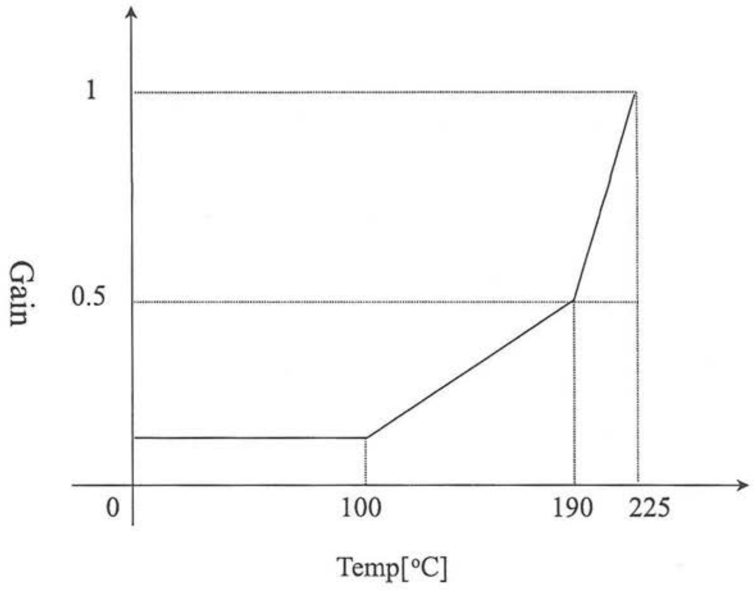


Figure 7. The proposed gain of water level controller with feedwater temperature variation.

The present valve position under operation, θ, can be referred to as the estimation of the feedwater flow rate and its difference from the reference valve position, $(\theta' - \theta)$, can be used for the corresponding fuzzy variable of the flow rate error.

3.3. A gain scheduler of feedwater temperature

The water level of the steam generator is varied by the temperature of feedwater. If the temperature of feedwater is low, then the shrink is appeared and the volume of steam generation is reduced. After a time delay, the water level returns to a normal level. Therefore we use a gain scheduler to compensate for the temperature variation of feedwater as Fig. 7.

3.4. Simulation results

In order to check the performance of the steam generator fuzzy controller by the proposed tuning method, simulations were performed Jung, C.H., Ham, C.S. and Lee, K.I. (1995), on the Compact Nuclear Simulator, 3-loop 993 MWe Westinghouse pressurized water reactor dynamics Kwon, Lyu, Malen and Skold (1988), installed in the nuclear training center of the Korea Atomic Energy Research Institute.

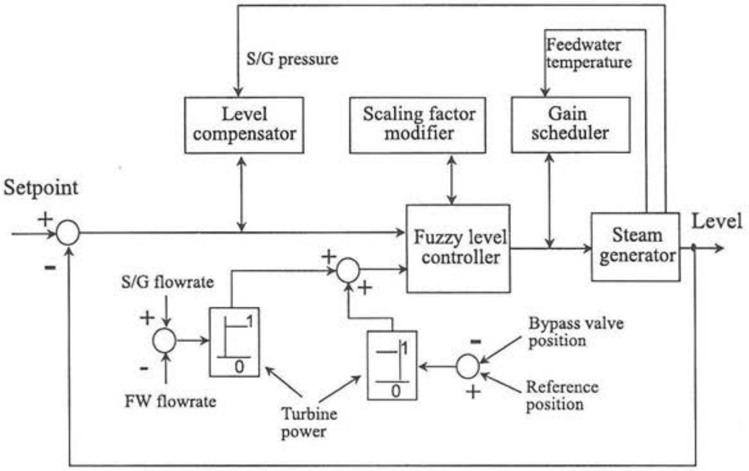


Figure 8. The block diagram of the proposed steam generator water level controller.

Index	Rise time(min)	Value	Sample no.
ρ_1	1	0.996666	300
ρ_2	4	0.998888	1200
ρ_3	7	0.999238	2100
ρ_4	10	0.999666	3000

Table 4. Reference tuning indices

The reference tuning indices in Table 4 are calculated for simulation on the assumption that the system has no time delay and 0.2 second sampling time. Increase or decrease in the quantity of scaling factor and weighting factor are 0.003 and 0.2 respectively in this simulation.

Fig. 9 shows the step responses of the steam generator water level at full power respectively. In Fig. 9, the response of the untuned fuzzy controller shows that it has a rise time which is too rapid and high overshoots. So it is necessary to maintain the rise time as rapid as possible and to reduce the overshoots for the short settling times.

The Bare 1 selects such a fast error ratio (ρ_1; low reference tuning index) that the response of water level shows a rather poor response, namely oscillations phenomena, than original response. Bare 2 selects a high reference tuning index(ρ_2) to have slow response, but it has a similar rise time and 1st over shoot as the untuned case. The proposed method uses ρ_1 and ρ_2 for the error above a 50% maximum error, and uses ρ_3 and ρ_4 for the error below a 50% maximum

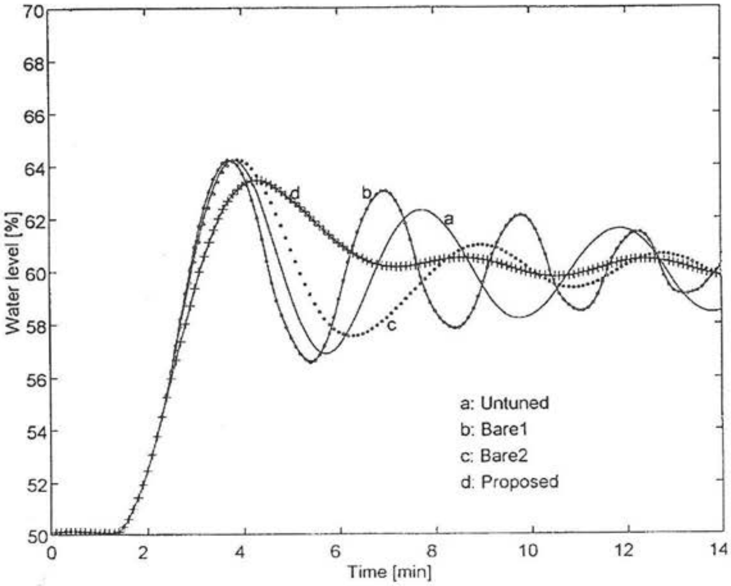


Figure 9. Step responses of water level for Untuned, Bare 1, Bare 2 and the proposed method)

No	Type	Rise time(s)	1st overshoot(s)	2nd overshoot(s)
a	Untuned	66.6	42.60	23.17
b	Bare1	65.0	42.86	30.25
c	Bare 2	67.8	42.45	9.65
a	Proposed	74.8	34.71	4.87

Table 5. The simulation results of tuning.

error. The water level response by the proposed method shows 18.5% reduction for 1st overshoot and 79% reduction for 2nd overshoot over the original response. The rise time by the proposed method has a slower response(12%) as expected than the untuned response. The rise time is not an important factor in this simulation, because the original response is too rapid. It is important to have small over shoots and fast settling time, because the steam generator has low and high water level trips. Table 5 shows the results of the simulation for the real-time tuning process. If we select a smaller universe of discourse for feedwater flow error than the above original untuned fuzzy controller used, the response of the new original untuned controller is very slow. In this situation, we can have a more rapid rise time and lower overshoots than new original response as expected by the proposed method. Fig. 8 shows the instantaneous system performance and Fig. 9 shows the scaling factor of error. The results show the performance of the controller is improved by the proposed tuning method.

If we select a smaller universe of discourse for feedwater flow feedwater flow error than the above original untuned fuzzy controller used, the response of the new original untuned controller is very slow. In this situation, we can have a more rapid rise time and lower overshoots than new original response as expected by the proposed method. Fig. 10 shows the scaling factors of a level error in this simulation. The results show the performance of the controller is improved in real-time by the proposed tuning method.

To show the effect of the pressure compensation rules by the proposed steam generator controller at low power, we changed 10% of steam pressure at 6% reactor power and compared with PI controller. The proposed method shows 27% reduction for overshoot and 26% reduction for the return time to normal level than PI controller as shown in Fig. 11. In this simulation, we can use the water level control rule which was used at full power tuning simulation. Because we used an image signal of feedwater flow error by the proposed method in this paper. For the simulation of the variation of the feedwater temperature, we assume that high pressure heaters are out of order. In this case the temperature of feedwater is changed from 227°C to 77°C at 100% reactor power. The simulation results of feedwater temperature variations show 46% reduction for overshoot and 14% reduction for the return time to return to a normal level

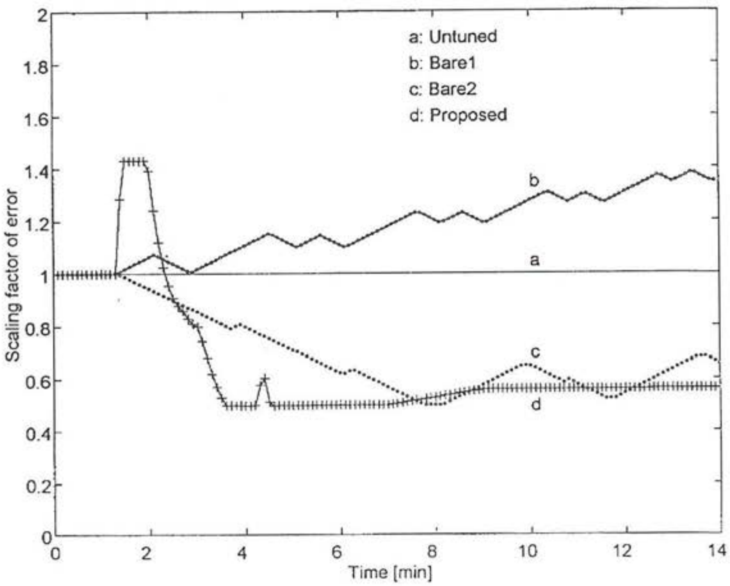


Figure 10. Scaling factors of error for untuned, Bare1, Bare 2, and the proposed method.

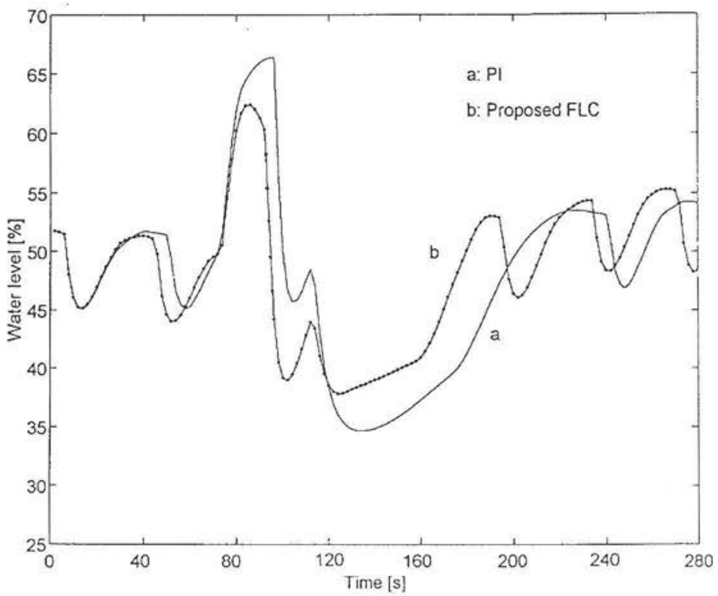


Figure 11. The response of water level of 10% steam pressure change for PI and the proposed method.

compared to PI controller as shown in Fig. 12.

4. Conclusions

In this paper, a fuzzy water level controller for a steam generator of nuclear power plant based on the real-time tuning of the scaling factors is presented. A new real-time tuning method of the scaling factors is proposed. The new tuning method uses a variable reference tuning index and an instantaneous system fuzzy performance. For the fuzzy water level controller design, an image signal of feedwater flow error at low power is proposed and a pressure compensation rule and a gain scheduler of feedwater temperature are designed. The results of the tuning of the fuzzy controller and the water level controls of the steam generator show good performance by the proposed method than others.

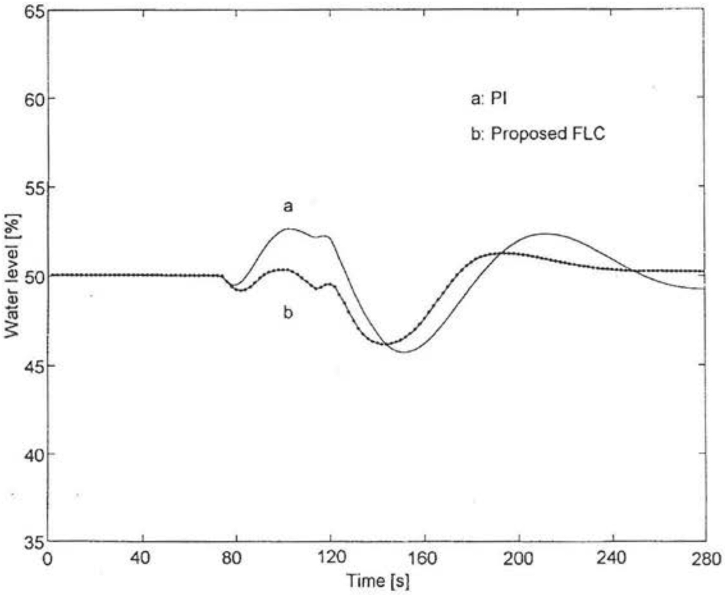


Figure 12. The response of water level of 77% feedwater change for PI and the proposed method.

References

AKIN, H.L. and ALTIN, V. (1991) Rule-based fuzzy logic controller for a PWR-type nuclear power plant. *IEEE Transactions on nuclear science*, **38**, 2, 883-890.

ALDRIDGE, J. (1992) Automated tuning and generation of fuzzy control systems. *ISA Transaction*, 15-17.

BARE, W.H., MULHOLLAND, R.J. and SOFER, S.S. (1990) Design of a self-tuning rule based controller for a gasoline refinary catalytic reformer. *IEEE Trans. on Automatic Control*, **35**, 2, 156-164.

DAUGHERITY, W., RATHAKRISHNAN, B. and YEN, J. (1992) Performance evaluation of a self-tuning fuzzy controller. *IEEE international conference on fuzzy system*, 389-397.

HAN, Y.J. and LEE, B.W. (1994) Fuzzy power control algorithm for a pressurized water reactor. *Nuclear Technology*, **106**, 242-253.

IKONOMOPOULOS, A. and TSOUKALAS, L.H. (1993) Applications of fuzzy methodologies in I and C. *Topical meeting on nuclear plant instrumentation, control and man-machine interface technologies, April, Oak Ridge, Tennessee*, 608-615.

JUNG, C.H., HAM, C.S. and LEE, K.I. (1995) A real-time self-tuning fuzzy controller through scaling factor adjustment for the steam generator of NPP. *Fuzzy sets and systems*, 53-60.

JUNG, C.H., HAM, C.S. and LEE, K.I. (1994) A real-time self-tuning fuzzy controller for a steam generator of NPP. *Proc. of Korea Nuclear Society Spring Meeting, Pohang, Korea*, **1**, 127-132.

KATAYAMA, R., KAJITANI, Y. and NISHIDA, Y. (1992) A self generating and tuning method for fuzzy modeling using interior penalty method. *Proceedings of the 2nd international conference on fuzzy logic and neural network*, 357-360.

KUAN, C.C., LIN, C. and HSU, C.C. (1992) Fuzzy logic control of steam generator water level in pressurized water reactors. *Nuclear Technology*, **100**, 125-134.

KWON, K.C., LYU, S.P., MALEN, K. *and* SKOLD, L. (1988) *KAERI Trainging Simulator Process Description*, July.

MAEDA, M. and MURAKAMI, S. (1992) A self-tuning fuzzy controller. *Fuzzy Sets and Systems*, **51**, 29-40.

PALM, R. (1993) Tuning of scaling factors in fuzzy controllers using correlation functions. *Proceedings of the 2nd IEEE international conference on fuzzy systems*, 691-696.

RAMASWAMY, P., EDWARDS, R.M. and LEE, K.Y. (1993) An automatic tuning method of a fuzzy logic controller for nuclear reactors. *IEEE Trans. on Nuclear Science*, **40**, 4, 1253-1262.

RUAN, D., D'HONDT, P., GOVAERTS, P. and KERRE, E.E. (1994) *Fuzzy Logic and Intelligent Technologies in Nuclear Science*. World Scientific, Singapore, 206-211.

SMITH, S. (1992) An algorism for automated fuzzy logic controller tuning. *IEEE International Conference on Fuzzy Systems*, 615-622.

TANJI, J., KINOSHITA, M., FUKUZAKI, T. and KOBAYASHI, Y. (1993) Application of fuzzy logic operation and control to BWRs. *Transactions of the American Nuclear Society*, **68**, 136-137.