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The Level Control System Design of the Nuclear Steam Generator for Robustness and Performance

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Abstract

The nuclear steam generator level control system is designed by robust control methods. The feedwater controller is designed by three methods of the H_∞, the mixed weight sensitivity and the structured singular value. Then the controller located on the feedback loop of the level control system is designed. For the system performance, the controller of simple PID whose coefficients vary with the power is selected. The simulations show that the system has a good performance with proper stability margins.

Key Words : steam generator, level control, robust control, H_∞ control

1. Introduction

The nuclear steam generator has a number of problems in the light of control design. These control problems directly arise from the physical characteristics of the steam generator. The mechanism of the steam generator is based on the thermal-hydraulic phenomena of heat transfer and fluid dynamics. The mathematical modeling of the thermal-hydraulic system is very difficult. Every mathematical model has uncertainties, more or less. But contrary to the electro-mechanical systems, the thermal-hydraulic systems have many intrinsic uncertainties, no matter how exactly it may be modelled. This is mainly due to the theoretical assumptions, linearizations, and experimental correlations. Further, the dynamics of the working fluid gives an additional uncertainty. For example, the valve actuators are usually non-linear, and their installation characteristics[1] are different depending on the actual piping configuration.

The heat transfer mechanism of the steam generator results in the shrink and swell effects. These effects are addressed by the control terminology of non-minimum phase. The control design of the non-minimum phase plant is more difficult than the unstable plant. The effect of the non-minimum phase becomes more salient, resulting in the difficulty in level control as the power becomes lower. This is due to the fact that the plant properties vary with the operation power, which imposes another problem on the control design. In addition to the uncertainties and adverse properties of the plant, the system configuration has two schemes. The feedwater station is a regulating system in that the feedwater flow rate should follow the system input signals of the steam flow rate. But the overall system is a regulating system in that the system output of level deviation should be kept constant.

There have been many studies on the steam generator level control system. The methods employed in those studies have a wide spectrum ranging from the classical PID[2], to the adaptive control including a gain scheduler[3],[4], to the fuzzy algorithms [5],[6] and to the AI techniques[7]. All these varieties rise from the plant uncertainty. Because the plant is uncertain, the recent attempts are focused on using the input-output relations without defining a plant itself. But these approaches have some limitations. While there are numerous sets of possible combinations of inputs and outputs, only the limited cases are to be considered in those algorithms.

The robust control method could be an alternative to the design of the steam generator level control system. The actual system should work as intended under the real circumstances even though it is designed with the inexact plant. The robustness is defined as the performance and stability for the family of plants which are exposed to the uncertainties. Hence the ultimate purpose of the control system is to maintain the robustness rather than the stability. However, it should be noted that too much stress on the robustness may result in the performance degrades. As the case may be, other control method gives the better results. In the control design, no method can definitely be the best, and compromises between various methods are required in accordance with the system characteristics.

The outline of this study runs as follows. First, the steam generator water level control system is described in brief. Then the feedwater control system which is a subsystem of the overall system is designed by various robust methods, followed by the feedback loop controller design. Finally, the simulations are made both for the power increase and decrease to show the system performance.

2. The Steam Generator Level Control System

Figure 1 shows the steam generator level control system. The overall system is a kind of regulating system in that the level variation should be kept constant. The steam flow rate change and other feedback signals generate a driving signal which controls the feedwater flow rate to keep the level constant. The feedwater station is a servo system in which the feedwater flow rate follows the steam flow rate.

The input and output of the steam generator plant are the feedwater flow rate change (ΔW_F) and level variation(ΔL), respectively. Several noises act on the plant. They are changes of primary coolant temperature(ΔT_P) and feedwater temperature(ΔT_F). Also it should be noted that the steam flow rate change(ΔW_F) is not only a command signal to the system but also is a disturbance to the steam generator. Therefore, the relationship between these inputs and the level, should be identified.

Eirving[8] set up the steam generator model which describes the relations between the level and feedwater flow rate, and between the level

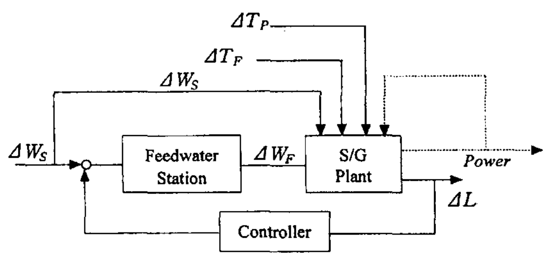

Fig. 1. Steam Generator Level Control System

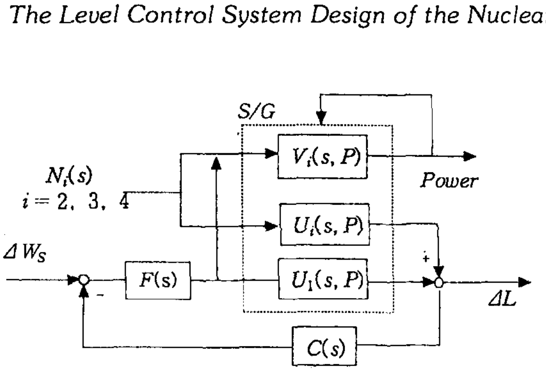

Fig. 2. The Block Diagram of the Overall Level Control System

and steam flow rate. His model shows the non-minimum phase which is related to the shrink and swell effects. However, it does not consider the fact that the steam generator properties depend on the power level, and the temperature effects are not considered either.

On the other hand, Lee[2],[9] developed the MIMO (multi-input, multi-output) transfer functions of the steam generator from the thermal-hydraulic code which describes the steam generator dynamics in detail. They describe the property changes of the plant. With these open loop transfer functions, the steam generator control system could be put into the block diagram of Fig. 2. In the figure, $U_i(s, P)$, i=1, 2, 3 ,4, are open loop transfer functions between the level and each element of input vector of $N_i(s) = [\Delta W_F(s), \Delta W_S(s), \Delta T_P(s), \Delta T_F(s)]$, respectively, and $V_i(s, P)$, i=1, 2, 3, 4, are open loop transfer functions between the percent power and the input vector. The feedwater station is represented as a single block $F(s)$. The characteristics of this system can be summarized as

1) the plant is dependent on its output, that is, the percent power, P
2) the system is comprised of the open loop for power and the closed loop for level
3) for the power loop train, all the input vector elements act as system inputs, and for the level train, $N_i(s)$, i=2, 3, 4 act on the system as disturbances
4) the system is MIMO. One of the system output is to be tracked, the other is to be regulated.

The overall control system design can be divided into two steps of the feedwater controller design and the feedback loop controller design.

3. Feedwater Controller Design

3.1. H_∞ controller

Since the feedwater control system is a servo system, at least one integrator is necessary. The valve station is assumed to be a first order lagger of time constant 1 sec. The rationales for this assumption are explained in Ref. [9]. Then the feedwater station of Fig. 1 could be recast as Fig. 3. The system uncertainty, d, and the measurement uncertainty, n, are described together. Figure 4 shows the singular values of the return difference and the inverse return difference when the controller is assumed as unity. With respect to the fact that the additive uncertainty, which is related to the return difference, is used to describe the high frequency model dynamics and the multiplicative uncertainty, which is related to the inverse return difference, is used for the low frequency actuator dynamics, it can be known that the multiplicative uncertainty imposes a more constraints on the feedwater station.

The feedwater system design is to find out the robust controller $H(s)$ in Fig. 3. For the robust design, Fig. 3 is reconstructed as the two-port model of Fig. 5. The system equations are posed as

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{21} w + D_{22} u \,. \end{aligned} \tag{1}$$

where $\boldsymbol{A}$, $\boldsymbol{B}_2$, $\boldsymbol{C}_2$ and $\boldsymbol{D}_{22}$ are system matrices of $G(s)$, $\boldsymbol{x} = (x_1, x_2)^T$ is the state variables vector, $\boldsymbol{w}$ is

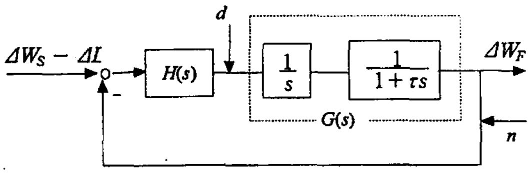

Fig. 3. Block Diagram of Feedwater Station

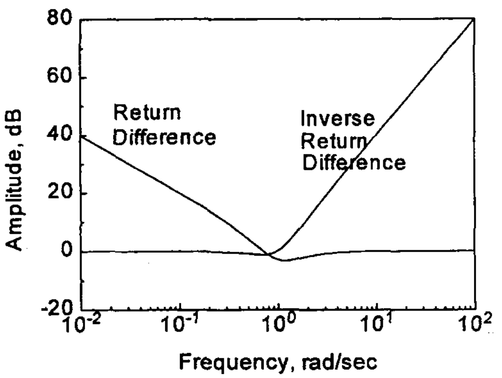

Fig. 4. Singular Values of Return Difference and Inverse Return Difference

the input vector of $(d \;\; n)^T$ and $\boldsymbol{z}$ is the regulated output vector of $(y_p \;\; u)^T$.

The packed matrix of Eq. (1) is

$$P(s) = \left(\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array}\right) = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix} = \begin{pmatrix} -1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & -1 & 0 & -1 & 0 \end{pmatrix} \quad (2)$$

This packed matrix is obtained with the assumption that the disturbance acts on the state variable x_1. Eq. (1) satisfies all the conditions for the existence of Riccati solutions. And the design of H_∞ controller is to find out the admissible controller $H(s)$ which makes the infinity norm of the overall closed loop system have a certain upper bound. That is,

$$\| \boldsymbol{T}_{zw} \|_\infty = F_l(\boldsymbol{P}, \boldsymbol{H}) < \gamma \quad (3)$$

where F_l $(\boldsymbol{P}, \boldsymbol{H})$ is the LFT (linear fractional

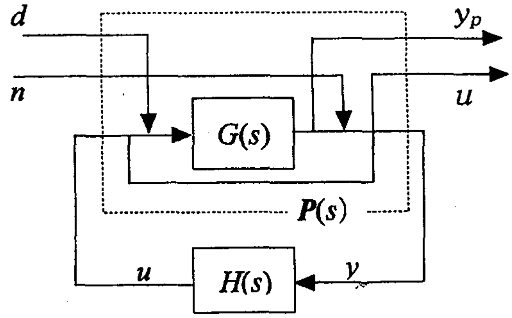

Fig. 5. Two-Port Model of Feedwater Control System

transformation) of the system which is defined as $\boldsymbol{P}_{11} + \boldsymbol{P}_{12}\boldsymbol{H}(\boldsymbol{I} - \boldsymbol{P}_{22}\boldsymbol{H})^{-1}\boldsymbol{P}_{21}$.

There are many reliable algorithms to calculate the controller[10],[11] and the controller is found to be

$$H_{\infty,1}(s) = \frac{5.414\times10^4 s + 5.899\times10^4}{s^2 + 3.138\times10^4 s + 6.758\times10^4} \quad (4)$$

with $\gamma = 1.7253$. This value of γ is calculated within the frame of H_∞ design.

The controller of Eq. (4) gives the PM (phase margin) of 67.4° and the GM (gain margin) of 91.5dB, which is sufficient to keep the system robustness. The regulated outputs of $(y_p \;\; u)^T$ converge rapidly to the steady state values, which shows the good robustness. Since the system $\boldsymbol{T}_{zw}$ is MIMO, it has two singular values and the infinity norm of the system is 1.

The controller $H_{\infty,1}(s)$ is determined with the assumption that the disturbance acts on x_1. But it is possible to configure the system in such a way that the disturbance acts on x_2. In this case, the packed matrix has different elements of

$$\boldsymbol{B}_1 = [0 \;\; 1]^T \quad (5)$$

and the controller is

$$H_{\infty,2}(s) = \frac{1.671\times10^4 s + 1.671\times10^4}{s^2 + 9090s + 2.166\times10^4}, \quad \gamma = 1.8392 \quad (6)$$

which gives the GM of 81.4 dB and PM of 72.8°.

It is informative to compare H_∞ controllers with LTR (loop transfer recovery) controller[9]. The H_∞ problem and LQG (linear quadratic Gaussian) problem have the same paradigm in that both problems are posed as a couple of Riccati equations. The difference between them is the norm used in the performance function. In the LQG, the performance function is the two-norm of output variance which is augmented by the state variable weighting matrix and control effort weighting matrix. The LQG problem is to find the stable controller which minimizes the two-norm of the system, and can be set as

$$\underset{Stable\ H(s)}{Min} \quad \| T_{zw} \|_2 \tag{7}$$

The LQG, which incorporates the observer, does not guarantee the margins of the LQR (linear quadratic regulation). However, Doyle[12] showed that the margins of LQR can be recovered with the LTR of

$$\lim_{q \to \infty} M(s)_{LQG} = M(s)_{LQR} \tag{8}$$

where $M(s)_{LQR} = K\Phi B$, $M(s)_{LQG} = K\Phi_r(s)LC\Phi(s)B$, $\Phi = (sI - A)^{-1}$, $\Phi_r(s) = (sI - A + BK + LC)^{-1}$, $E(ww^T) = Q_0 = q^2 BB^T$.

To obtain the target loop of $M(s)_{LQR}$, the feedwater servo system is converted to a regulating system by the transformation of

$$\dot{\xi} = A\xi + Bw, \quad \zeta = C\xi + Dw, \quad w = -K\xi$$
$$A = \begin{pmatrix} a & b \\ 0 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ b \end{pmatrix}, \quad C = (c,\ 0), \quad D = 0 \tag{9}$$

where (a, b, c) is the system matrix of the first order valve station.

From Eq. (9), the integrator gain and feedback gain are found to be [1.0 0.7321], and the LQR has the target PM of 81°. With this target loop, and by controlling the noise spectral density of

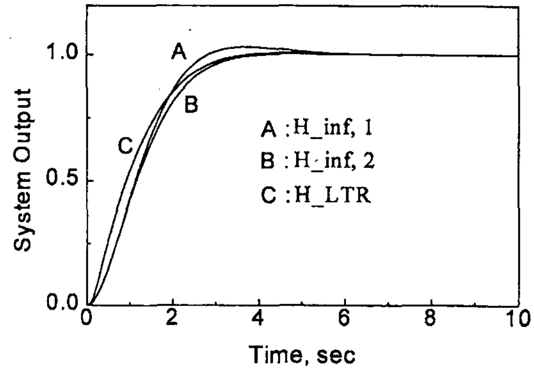

Fig. 6. Unit Step Responses of Feedwater Station for Various Controllers

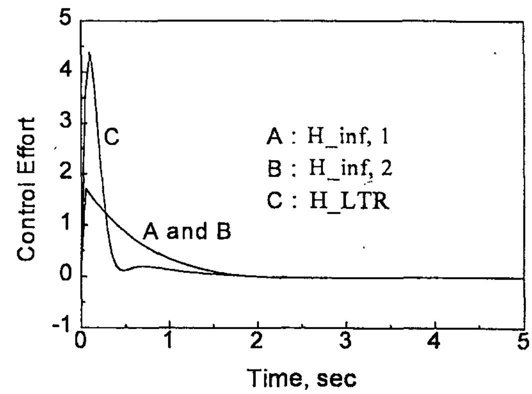

Fig. 7. Control Efforts of Feedwater Station for Various Controllers

$q^2 BB^T$, where $B = [b\ 0]^T$, the LTR controller is determined as Eq. (10) and has the PM of 77° and GM of 28 dB.

$$H(s)_{LTR} = \frac{114.1884\,s + 150}{s^2 + 18.0814\,s + 162.97} \tag{10}$$

Figure 6 shows the unit step responses of the feedwater system incorporated with each controller designed so far. Comparing $H_{\infty 1}(s)$ with $H_{\infty 2}(s)$, it can be known that the speeds of the both are almost the same, but $H_{\infty 2}(s)$ gives the shorter settling time than $H_{\infty 1}(s)$. Also there is no overshooting for the case of $H_{\infty 2}(s)$. The $H(s)_{LTR}$

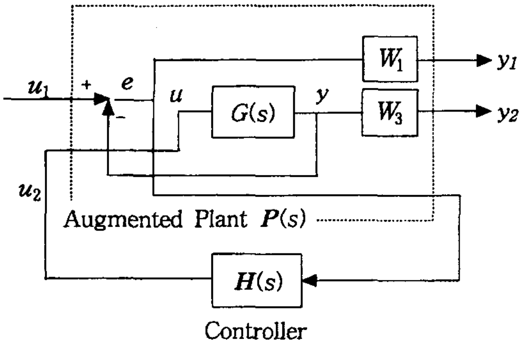

Fig. 8. Two-Port Model with Augmented Weights

seems to be superior to $H_{\infty,1}(s)$ or $H_{\infty,2}(s)$ in the speed and settling time. But as shown in Fig. 7, the control effort of the $H(s)_{LTR}$ is much larger than those of H_∞ controllers, which is not desirable with respect to the actuator movement. Accordingly, $H_{\infty,2}(s)$ is adopted as a finally designed controller.

3.2. Robust Controller by MWS

The robust controller can be designed by other offsprings of the H_∞ control algorithms. One of them is the MWS (mixed weight sensitivity) based on the classical loop shaping[13],[14]. The unity feedback system of Fig. 3 can be described by the two-port model of Fig. 8 with the augmented weights.

Considering the external command signal only, the system transfer function is the SIMO(single input, multiple output) of

$$T = \frac{(y_1 \;\; y_2)^T}{u_1} = \begin{pmatrix} W_1 S \\ W_3 T \end{pmatrix} \tag{11}$$

where S and T denote the sensitivity and complementary sensitivity, respectively.

The MWS problem is to determine the stable controller which makes the infinity norm of the closed loop system minimum by selecting proper weighting functions. W_1 and W_3 are functions of frequency, and they are major design factors in MWS. For the desirable loop shapes, they should be determined to satisfy the following conditions.

$$\bar{\sigma}(S(j\omega)) \le |W_1^{-1}(jw)|, \quad \bar{\sigma}(T(j\omega)) \le |W_3^{-1}(jw)| \quad \forall\, \omega \tag{12}$$

where $\bar{\sigma}(\cdot)$ is the singular value.

The MWS requires numerous iterations because the designed system is sensitively related to the selection of weighting functions. And because the H_∞ algorithm are non-convexing problem, it is very difficult to determine the optimal weighting functions.

The MGA (modified genetic algorithm)[14],[15], which is an efficient optimizing tool in the non-convexing problem, is applied to determine the weighting functions. The objective function of the GA is

$$C = \sum_{t=0}^{\infty}(\alpha_1|y(t)-y_s| + \alpha_2|u(t)-u_s|), \quad \text{with } \alpha_1 = \alpha_2 = 1 \tag{13}$$

With this objective function, the weighting functions are calculated as

$$W_1(s) = \frac{1}{\gamma_1}\cdot\left(\frac{s+0.4049}{0.5092}\right),$$
$$W_3(s) = \frac{1}{\gamma_3}\cdot\left(\frac{s^2+2.3833s+1.8388}{s^2+2.3835s}\right) \tag{14}$$
$$W_2(s) = \frac{1}{\gamma_2}, \quad \gamma_1=0.1, \;\; \gamma_2=0.2 \;\text{ and }\; \gamma_3=5$$

$W_2(s)$ is applied to the control input to meet the system rank conditions for the solution existence. Then, Eq. (11) is set into the canonical form of Eq. (1), and the controller is calculated in line with the H_∞ algorithms as

$$H(s)_{MWS} = \frac{15.2s^2+113.3s+98.05}{s^3+13.12s^2+80.79s+131.6} \tag{15}$$

The singular values of the sensitivity(S) and

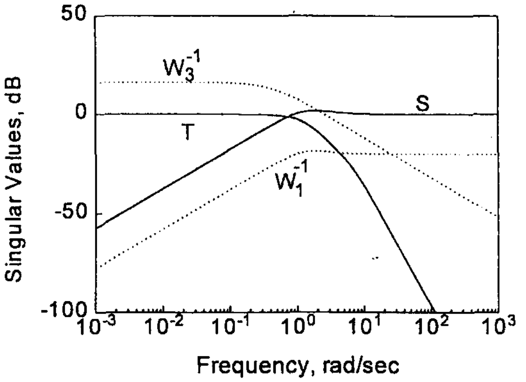

Fig. 9. Singular Values of T and S with Weighting Functions

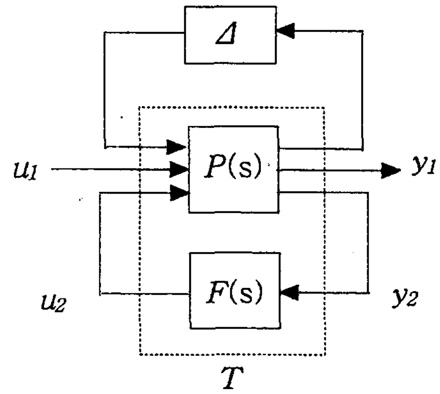

Fig. 10. Δ-P-F System

complementary sensitivity(T) of the designed system are described in Fig. 9, together with those of weighting functions. In the figure, the singular values of the sensitivity is larger than those of W_1^{-1}. Although the design proceeds with the constraint of $\bar{\sigma}(S(j\omega)) \le |W_1^{-1}(j\omega)|$, the results may be different, since the constraint is only a guide for the loop shaping.

The simulation shows that the unit step response and the control effort of the $H(s)_{MWS}$ system are almost the same as those of the $H_{2,\infty}(s)$ system. But because of the augmentation of weighting function, the order of the controller increases to the third order (exactly, it is the fourth order but through the model reduction, it becomes of the third order). Also it should be noted that the $H(s)_{MWS}$ could be different depending on the objective function used in the GA. For example, if the larger penalty is given to the output, the system speed increases but at the expense of the larger control effort.

3.3. Robust Controller by μ-Synthesis

In addition to the H_∞ and MWS controller, another robust algorithm of the structured singular value methods or μ-synthesis[16] is applied too. The stability and performance of the robust system are represented by the analysis and synthesis problems, respectively. The former is concerning to the verification of the controller stability for the given uncertainties, and the latter is to the determination of the stable controller which maintains the required performance. The stability problem is based on the Nyquist small gain theorem. In Fig. 10, T denotes the feedback system, and Δ stands for the uncertainty.

If $\|\Delta\|_\infty$ is less than $\frac{1}{\|T\|_\infty}$, the perturbed system is stable. The characteristics of this system is that the singular value of the uncertainty is not so sensitive to the uncertainty itself. On the other hand, the synthesis problem is to find out the controller which satisfies the following condition.

$$\begin{aligned} &\|T_{zw}\|_\infty \le 1, \quad \text{for all } \Delta \in \boldsymbol{B}_\Delta \\ &= \{\Delta \in \boldsymbol{\Delta}, \ \|\Delta\|_\infty < 1\} \quad \forall \omega \\ &z = [y_1, \ y_2]^T, \ w = [u_1, \ u_2]^T \end{aligned} \tag{16}$$

The MIMO closed loop system T_{zw} is obtained by the fractional transformation of

$$\begin{aligned} T_{zw} &= F_l(F_u(G, \Delta), F) \\ &= F_u(F_l(G, \Delta), F), \ G = \text{plant} \end{aligned} \tag{17}$$

Table 1. Key Parameters of μ Iteration

	Case	Controller	Margins	
1	1st Iteration : D_0 2nd Iteration : D_0	$\frac{4498(s+1)}{s^2+1721s+4351}$	64.4dB	69°
2	1st Iteration : D_0 2nd Iteration : D_1	$\frac{3.044\times10^4 s^5+..+4.166\times10}{s^6+1.627\times10^4 s^5+..+5.473\times}$	86.4dB	74°
3	1st Iteration : D_1 2nd Iteration : D_0	$\frac{4498(s+1)}{s^2+1721s+4351}$	64.4dB	69°
4	1st Iteration : D_1 2nd Iteration : D_1	$\frac{2.838\times10^5 s^5+..+1.51\times10^4}{s^6+1.488\times10^5 s^5+..+1.977\times}$	106dB	76°

D_o : constant scaling matrix, D_1 : first order scaling matrix

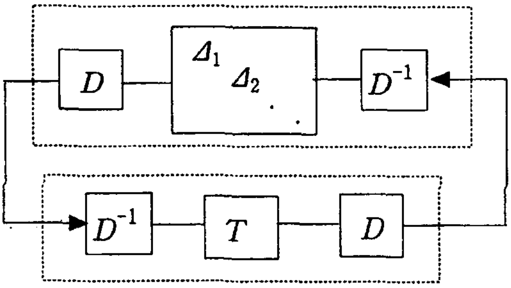

Fig. 11. Diagonal Scaling Augmentation

The structured singular value (SSV) is defined as

$$\mu_\Delta(T)=\frac{1}{inf_\Delta\{\bar{\sigma}(\Delta) \mid det(I-T\Delta)=0\}} \quad (18)$$

By using this definition, the synthesis problem is to determine the stable controller $F(s)$ which makes

$$\mu_\Delta(T)\leq 1 \quad (19)$$

One of the SSV properties is that the SSV has the bound of

$$\rho(T)<\mu(T)<\bar{\sigma}(T), \quad \rho(\cdot) = \text{spectral radius} \quad (20)$$

When the uncertainty is of the full block matrix, that is, $\Delta \subset C^{n\times n}$, the upper bound of Eq. (20) tends to have a very large value. And the design with this wide bound results in a too conservative controller. To remedy this over-conservativeness, a scaling matrix is augmented as in Fig. 11. As in the figure, the infinity norm of ΔT does not change, but $\| D^{-1}TD \|_\infty$ can be reduced. Therefore, the design purpose is to determine the $F(s)$ and D which satisfy

$$\mu(T_{zw})\leq \inf_{D\in \mathbf{D}} \| DT_{wz}D^{-1}\|_\infty \leq 1 \quad (21)$$

The controller is designed by the following procedures.

Step 1 : Determination of T_{zw} by H_∞ method with *initial packed matrix P(s)*

Step 2 : Augmentation of scaling matrix D to T_{zw}, say, $P_i(s)=DT_{zw}D^{-1}$

Step 3 : With this augmented packed matrix, repeat steps 1 and 2, until the specification is satisfied, or the results saturate

Several calculations are made with the constant D and the first order D. For example, the constant D is augmented in the first iteration, and the first order one is used in the second iteration, so on. Some of the results are summarized in Table 1. The order of the controller depends on the D which is used in the final iteration.

Two cases of 1 and 3, whose iterations end with the constant D, are the same. They give the more improved performance than the controller $H_{\infty,2}(s)$ of Eq. (6), but at the expense of the larger control effort (increases by 43%). For the cases of 2 and 4, the performance is almost the same as that of $H_{\infty,2}(s)$, and the margins are slightly increased. But the controller order is of the sixth, which is not desirable for the implementation. In summary, the feedwater controller of $H_{\infty,2}(s)$ seems to be the most proper one among several candidates with respect to various control specifications.

4. Feedback Controller

With the feedwater controller of Eq. (6), the feedwater station, F(s), is represented as

$$F(s) = \frac{1.6714\times10^{4}(s+1)}{s^{4}+9091s^{3}+3.0746\times10^{4}s^{2}+3.8371\times10^{4}s+1.6714\times10^{4}} \quad (22)$$

By letting $G(s) = F(s)\ U_1(s, P)$, and by treating the effects due to $U_i\ (s, P)$ (i = 2,3,4) as disturbances, the level control system of Fig. 2 can be simplified as Fig. 12. And this scheme can easily be fashioned into the two port model of Eq. (1) with the coefficients of

$$G(s) \leftrightarrow [A,\ B,\ C,\ D],$$

$$B_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T,\quad B_2 = -B,\quad C_1 = \begin{pmatrix} & & C & & & \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T, \quad (23)$$

$$D_{11} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix},\ D_{12} = \begin{pmatrix} 0 \\ 0 \end{pmatrix},\quad C_2 = C,\quad D_{21} = (0\ \ 1),\quad D_{22} = 0$$

For the initial steady state power of 5%, the H_∞ controller is found to be

$$C(s) = \frac{2.174s^{5}+1.976\times10^{s^4}+4.734\times10^{4}s^{3}+3.692\times10^{4}s^{2}+468.7s+19.26}{s^{6}+9092s^{5}+3.57\times10^{4}s^{4}+5.034\times10^{4}s^{3}+2.624\times10^{4}s^{2}+339.3s+13.76} \quad (24)$$

and has the PM of 89.2° with the GM of 36dB.

This margin is too large, and the system performance degrades to the impracticability. To improve the performance, an additional gain could be introduced. For example, the gain of 30 results in the PM margin of 65° with the plausible speed as described in Fig. 13. But this gain value gives no effects when the power is high. As the power increases, the plant becomes more stable, hence the gain should be increased to maintain the same effects. To keep the same performance as above at 30% power, the gain should be increased to around 120, if the controller designed at 5% power is used.

With an additional gain, the design factors are gain values and the controller coefficients of Eq. (24). The gain value control depending on the power conforms with the concept of gain scheduling. But it is very difficult to provide the system with the flexibility only by gain control. On the other hand, the H_∞ controller becomes different with the power

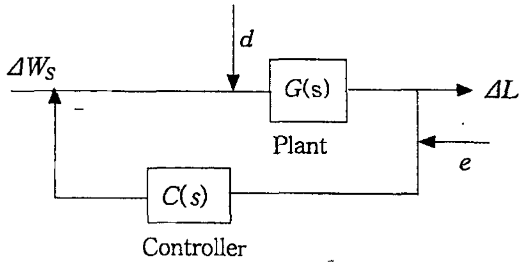

Fig. 12. Level Control System with Feedback Controller

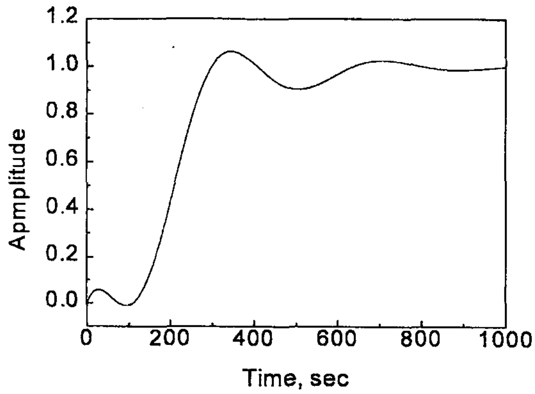

Fig. 13. Level Responses for the Unit Step Steam Flow Rate (5%, K=30)

since the plant varies with the power. And the control of controller coefficients with continuously varying power is impractical, since the order of the controller is too high.

Instead of the H_∞ controller, it is found that the PID controller which was proposed in Ref.[9] is more practical since the number of coefficients to be controlled is only two. The proposed controller is

$$C(s,P)=\left(K_p(P)+\frac{K_i(P)}{s}\right),\ K_p(P)=34.26+3.85P+0.2P^2$$
$$K_i(P)=\frac{K_p(P)}{641.3-60P+2.1P^2},\ P=\text{power in percent} \quad (25)$$

With this controller, the system has an almost constant PM of about 30° for the power range of 1% to 30%, and the GM increases slightly from 3dB at 1% power to 5dB at 30%. For the power range of over 30%, the designed controller yields the larger margins and another controller might be defined. However, since the steam generator level control is an issue in low power range, the controller of Eq. (25) is selected as a feedback loop controller.

5. Simulations and Discussions

In Fig. 2, the changes of feedwater flow rate (ΔW_F) and level(ΔL) are calculated by

$$\Delta W_F(s)=\frac{\Delta W_S(s)F(s)\{(1-C(s,P)U_2(s,P))-F(s)T(s,P)}{1+F(s)U_1(s,P)C(s)} \quad (26)$$

$$\Delta L(s)=\frac{\Delta W_S(s)(U_2(s,P)+U_1(s,P)F(s))+T(s,P)}{1+F(s)U_1(s,P)C(s)} \quad (27)$$

where $T(s,P) = T_P(s,P)\,U_3(s,P) + T_F(s,P)\,U_4(s,P)$

And the power included in the transfer functions are obtained from

$$P(t)=L^{-1}\left[\sum_{i=1}^{4}V_i(s,P)N_i(s)\right],\ N_1=\Delta W_F, \quad (28)$$
$$N_2=\Delta W_S,\ N_3=\Delta T_P,\ N_4=\Delta T_F$$

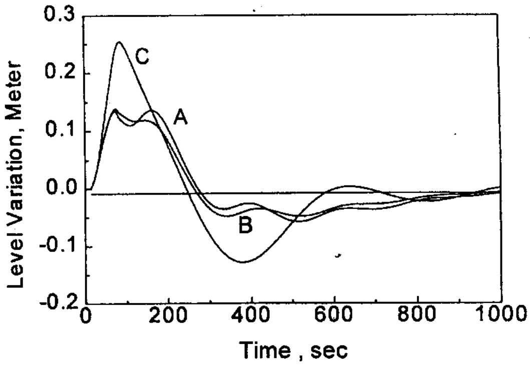

Fig. 14. Level Transients, From 5% to 10% Power Increase

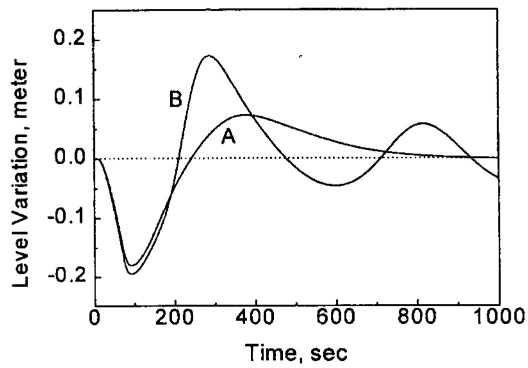

Fig. 15. Level Transients, From 10% to 5% Power Decrease

The level deviation and feedwater flow rate change are calculated by the above equations together with the designed controllers of Eq. (6) and Eq. (25). The calculation procedure is :

Step 1 : Determination of $U_i(s,P_0)$, $V_i(s,P_0)$, i = 1, 2, 3, 4 and $C(s,P_0)$ at the initial power P_0

Step 2 : Determination of system input variables of $\Delta W_S(t)$, $\Delta T_P(t)$ and $\Delta T_{FW}(t)$ at time $t=t_0$

Step 3 : Calculation of system output of $\Delta L(t)$, $\Delta W_S(t)$ and $P(t)$

Step 4 : Determination of $U_i(s,P(t))$, $V_i(s,P(t))$, i = 1, 2, 3, 4 and $C(s,P(t))$

Step 5 : Iteration of step 2 through 4.

The simulations are made in parallel with those of Ref.[9] for the comparison. Two situations are simulated. One is the power increase from 5% to 10% and the other is the power decrease from 10% to 5%. The input conditions are the same as those of Ref. [9]. Also as in Ref.[9], three cases are considered. Case A is such that all the transfer functions and the controller varies with the power. Case B is such that the transfer functions varies continuously with the fixed controller, while in Case C, the transfer functions and controllers determined at the initial power are assumed to be fixed during the transients. In short,

Case A : $H_i(s,P) = H_i(s,P(t))$, $P_i(s,P) = P_i(s,P(t))$, $C(s,P) = C(s,P(t))$

Case B : $H_i(s,P) = H_i(s,P(t))$, $P_i(s,P) = P_i(s,P(t))$, $C(s,P) = C(s,P_0) = Const$

Case B : $H_i(s,P) = H_i(s,P_0)$, $Const$, $P_i(s,P) = P_i(s,P_0) = Const$, $C(s,P) = C(s,P_0) = Const$

Figure 14 shows the level variation for each case when the power is increased. Case C shows that if the variation of the plant properties are not considered, the control design is meaningless. Case A and B show the similar level responses. But the transients of Case B is somewhat milder than those of Case A. Further, although not shown in the figure, the feedwater transients of Case A is severer than those of Case B. In summary, Case B shows a little better dynamics than Case A. This is due to the fact that the controller determined at the low power gives a larger margins at high power. Comparing these results with those of Ref.[9], the overall trends are quite similar. But while the Case A in Ref.[9] shows the unstable oscillations, the responses of Case A in this study show a good stability.

The level transients for the power decrease are described in Fig. 15. Case C is not considered since it is unrealistic. Contrary to the power increase, Case A shows the milder results than Case B. The dynamics of the two cases are almost the same as those of Ref.[9], but the peak values of both cases decreases by 5 to 8% from those of Ref.[9].

6. Conclusions

The control system design starts from the exact description of the plant to be controlled. But all the plant model have uncertainties. The control system based on the uncertain plant might not work in the actual situation. The robust control takes the uncertainties into account as one of the design factor, and makes the system maintain the sufficient robustness in the real world. The steam generator model has many uncertainties due to its thermal-hydraulic properties. Also its properties change with the power, which gives another difficulty in defining the model.

To make allowances for the uncertainty of the steam generator, various methods are applied to the control system design. Among various methods, the H_∞ method with controlling the state variables is found to be the most appropriate one for the feedwater controller design. The output response of the robust controller is almost the same as that of the LTR controller, but the robust controller decreases the control effort significantly. In contrast with the feedwater station, the robust control method is not proper for the design of the feedback loop controller. In the control design, various specifications should be considered. Although the designed system has sufficient robustness, its performance is impractical, and the order of the controller is too high.

The power dependent PID is preferable to the robust controller in the light of various control specifications. The simulations are made for both cases of power increase and decrease. The results show a good performance with proper stability margins. However, since the plant varies through the transients, different operational mode is recommended. That is, for the case of power increase, the controller determined at the initial stage of transients is to be fixed, and for the case of power decrease, the controller is to be varied with the power.

Also it should be noted that the uncertainty in flow measurement is not considered in this paper. The steam flow rate signal acts as the command signal and the feedwater flow rate signal is a feedback signal in the system. Since the feedwater flow rate is uncertain, particularly under the nominal rate, a Kalman filter could be proposed to eliminate the measurement noises in further study.

References

1. R. N. Bateson, *Control System Technology*, pp. 406-410, Prentice-Hall (1996).
2. Y. J. Lee, U. C. Lee, "Digitalization of the Nuclear Steam Generator Level Control System," *J. of KNS* (**25**)1, pp. 125-135 (1993).
3. J. H. Yun et al., "A Study on Improvement of PWR S/G Water Level Control at Low Power Operation," *J. of KNS* (**26**)3, pp. 420-424 (1994).
4. C. H. Kim et al., "Self-Tuning Predictive Control with Application to Steam Generator," *J. of KNS* (**27**)6, pp. 833-844 (1995).
5. B. S. Moon et al., "Fuzzy Algorithms to Generate Level Controllers for Nuclear Power S/G," *J. of KNS* (**25**)2, pp. 222-232 (1993).
6. N. J. Na, Z. Bien, "A Fuzzy Controller for the S/G Water Level Control and Its Practical Self-Tuning Based on Performance," *J. of KNS* (**27**)3, pp. 317-326 (1995).
7. J. G. Lee, J. Y. Choi, "Modeling of Nuclear Power Plant S/G using Neural Networks," *J. of Cont., Aut. and System*, **4**(4), pp. 551-560 (1998).
8. E. Eirving et al., "Towards Efficient Full Automation Operation of the PWR Steam Generator with Water Level Adaptive Control," Boiler Dynamics and Control in Nuclear Power Station 2, British Nuclear Energy Society, pp. 309-330 (1990).
9. Y. J. Lee, "The LQR/LTR Dynamic Digital Control System Design for the Nuclear S/G Water Level," *J. of KNS* (**27**)5, pp. 730-742 (1995).
10. M. A. Daleh, I. J. Diazo-Bobillo, *Control of Uncertain Systems*, pp. 145-183, Prentice-Hall (1995).
11. R. S Sanchez-Pena, M. Sznier, *Robust Systems - Theory and Application*, pp. 157-206, John Wiley and Sons (1998).
12. J. C. Doyle, G. Stein, "Robustness with Observers," *IEEE Trans. on Aut. Cont.* 24, pp. 607-611 (1979).
13. J. M. Maciejowski, *Multivariable Feedback Design*, pp. 16-19, Addison Wesley (1989).
14. Y. J. Lee, K. H. Cho, "Determination of Weighting Parameters of the LQR System for Nuclear Reactor Power Control using the Stochastic Searching Methods," *J. of KNS* **29**(1), pp. 68-77 (1997).
15. Y. J. Lee et al., "Robust Design of Reactor Power Control System by Genetic Algorithm-Applied Weighting Functions," *J. of KNS* **30**(4), pp. 353-363 (1998).
16. J. C. Doyle, "Analysis of Feedback Systems with Structured Uncertainties," *Proceedings of the Institution of Electrical Engineers*, Pt. D 133, pp. 45-56 (1982).