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Digitalization of the Nuclear Steam Generator Level Control System

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증기발생기 수위조절 시스템의 디지탈화

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Abstract

The safe and efficient operation of nuclear plants is recognized to be accomplished through the application of plant automation using digital technology, which is one of main targets of the next generation nuclear plants. For plant level automation, it is first required that each major subsystem be digitalized, and the steam generator water level control system is discussed in this study. The transfer functions between inputs and the level are derived by employing the thermal hydraulic model of the steam generator and are applied to the analysis of the current three-element control system. Since the control scheme in this study includes the steam generator itself as a process plant, the system order is high and the numerical instability arises in digitalizing. Together with this, the unreliability of the feedwater feedback signal at low power level leads to the proposal of a two-element control system with a proper digital controller. The digital PI controller developed for this system has the initial power adaptive gain and integration time constant. And it makes the overall system response satisfy the stability and other necessary control specifications simultaneously. Since the two-element control system using this controller depends on the initial power only, it is simple to define and it shows a similar level response behavior to that of its corresponding analog system.

요 약

안전하고 효율적인 원자력 발전소의 운전은 디지탈 기술을 이용한 발전소 자동화로 이루어질 수 있다는 인식과 함께 이같은 발전소 자동화는 차세대 원자력 발전소의 중요한 목표중의 하나가 되고 있다. 전체적인 발전소 수준의 자동화를 위해서는 일차적으로 각 주요 시스템에 대한 디지탈화

가 요구되며 본 논문에서는 증기발생기의 수위조절 시스템에 대해 연구하였다. 이를 위해 증기발생기의 열수력학적 모델을 이용하여 증기발생가에 작용하는 여러가지 입력과 수위와의 관계를 전달함수로 표시하였으며 이를 이용하여 기존의 발전소에서 사용되고 있는 3 요소 제어시스템을 검토하였다. 본 논문에서의 제어구성은 증기발생기 그 자체를 시스템내에 플랜트로서 포함시킨 것이기 때문에 전체적인 시스템 차수가 증가하며 디지탈 과정중 수치적 불안정이 야기된다. 이러한 문제와 아울러 저출력에서는 궤환신호로 작용하는 급수유량의 신뢰도가 작음을 고려하여 2 요소 제어시스템 및 그에 따른 디지탈 제어기에 대해 연구하였다. 이 시스템의 디지탈 비례적분제어기는 그 이득 및 적분시간상수가 초기출력에 따라 변하며 전체적인 시스템의 응답특성이 안정성 및 기타 제어특성을 동시에 만족시키도록 하고 있다. 이러한 제어기를 사용한 2 요소 제어시스템은 초기출력에만 의존하므로 정의하기가 간단하며 또 이러한 시스템의 수위응답은 그에 대응하는 아날로그 시스템의 결과와 비슷함을 보이고 있다.

1. Introduction

The increasing demands by safety and environmental regulations, together with the demands of the economic aspect, inevitably lead to more sophisticated plants with more systems. The safe and efficient control of the nuclear plants is recognized to be achieved by the application of the automation using digital systems and this automation is one of the main objectives of the next generation nuclear plants.

At present, the instrumentation and control systems of a large number of nuclear plants employ the analog technique which has been developed since the 1960s. The analog systems provide a simple method of controlling nuclear power plants. And their reliability and stability have improved with the introduction of solid state technology. However, digital systems have demonstrated error–free performance that is at least two orders of magnitude better than analog systems performing the same function [1]. Moreover, analog systems have additional problems, for example, the replacement of obsolete parts and the difficulty of utilizing modern control techniques which is required for plant automation [2], [3].

To automate the entire plant, it is necessary to set up a digital control system for each major subsytem. The steam generator level control system is therefore discussed in this study. The level control of a steam generator is characterized by the thermal hydraulic properties, one of which is the swell and shrink phenomenon which adversely affects the control efforts. This phenomenon becomes more salient as the power becomes lower and may trigger unintended trips.

The purpose of this study is to design a digital control system by which the level control could be accomplished for all power ranges, and thus could eliminate the problems described above. The relationship between various inputs to the steam generator and the output (the level) are examined to establish the power adaptive open loop transfer functions which can precisely describe the thermal hydraulic effects.

With these open loop transfer functions, the typical three–element control system commonly used in current nuclear plants is modeled. This model includes the steam generator as a process plant. By introducing samplers and holders, it is then digitalized. The numerical instabilities arising from digitalizing are checked with respect to the system order. Considering further the unreliability of feedwater flow rate at low power, a new two–element control scheme is proposed with a proper digital controller which can satisfy the control specifications and yield the desirable system responses.

2. Open Loop Transfer Function Model

There are four inputs to the steam generator which are related to the output, viz., the water level. These are feedwater flow rate, steam flow rate, primary coolant temperature, and feedwater temperature. If the relations between each input and output were defined, that is, if the control plant or control process could be described, then it would be possible to construct a control system which satisfies a given control specification. This system identification is made employing the thermal hydraulic model of a 857 MWt Westinghouse F–type steam generator[4],[5]. The relations between inputs and the output are expressed in the form of transfer functions, which is the same procedure as those of References [6] and [7]. However those transfer functions are refined more exactly in this study.

At a given power, the input is step changed by half of its steady state value. Then the level is calculated by the thermal hydraulic model of the steam generator. The calculated level is divided again by the amount of change in order to get the unit step change response (level per kg/sec for flow rates or level per degree for temperatures).

Figures 1(a) and 1(b) describe respectively the net effects of shrink and swell obtained by this thermal hydraulic calculation for the initial powers of 5%, 10% and 15%. It is to be noted that the effect of swelling is much larger than that of shrink because of the difference of the specific volumes between steam and feedwater.

Besides the effects from mass flow rate changes, the primary coolant temperature and the feedwater temperature also affect the level change. As a result of these thermal hydraulic characteristics, the gain of false response and the phase lag of feedwater to the level become larger as the power decreases. Also the settling time gets longer with the decrease of power level. All of these cause the difficulty of low power operation.

The transfer function for the relation between the feedwater flow rate and the level is

$$H_1(s) = \frac{K_1}{s} + A_1 \frac{a_1^2}{(s + a_1)^2} + B_1 \frac{b_1^2}{(s + b_1)^2} \exp(-d_1 s) \quad (1)$$

The first term denotes the direct response to feedwater flow rate and the other terms describe the shrink effect. All the constants in the above equation are functions of the power levels and are summarized in Table 1. The transfer functions for steam flow rate (H_2), primary coolant temperature (H_3), and feedwater temperature (H_4) are

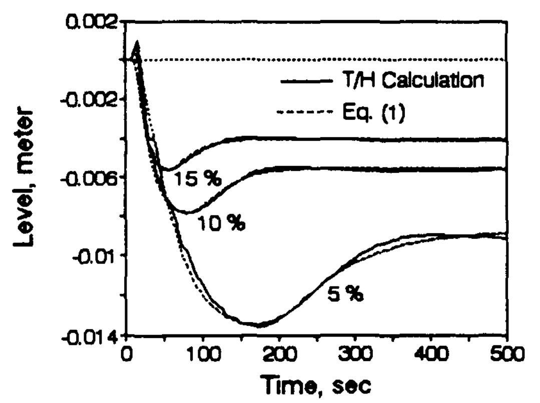

Fig. 1a. Net Shrink Effect by Unit Step Increase (1Kg/sec) of Feedwater Flow Rate

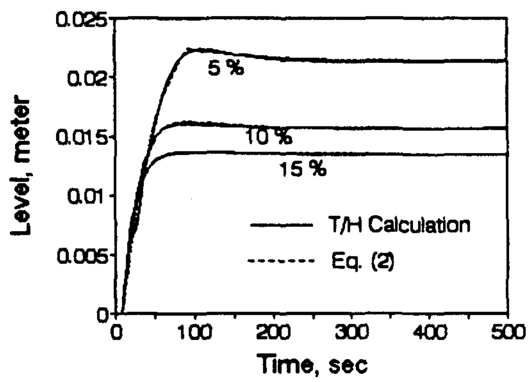

Fig. 1b. Net Swelling Effect by Unit Step Increase (1Kg/sec) of Steam Flow Rate

$$H_2(s) = \frac{K_2}{s} + A_2 \frac{a_2}{(s + a_2)} + B_2 \frac{b_2}{(s + b_2)} \exp(-d_2 s) \quad (2)$$

$$H_3(s) = \left[A_3 \frac{(a_3 - b_3)\, s}{(s + a_3)(s + b_3)} + B_3 \frac{c_3}{(s + c_3)} \right] \exp(-d_3 s) \quad (3)$$

$$H_4(s) = A_4 \frac{\omega_n^2}{s^2 + 2\, a_4 \cdot s + \omega_n^2} \quad (4)$$

The results calculated by Eqs.(1) and (2) are also described in Figures 1(a) and 1(b) respectively for the comparison with the results of thermal hydraulic calculation. As shown in the figures, good agreements result.

The open loop transfer functions above are expressed in s domain and they are z–transformed by introducing the zero order holder (ZOH) and sampler. For example, the z–transformed transfer function $H_1(z)$ is

$$H_1(z) = Z[ZOH(s) \cdot H_1(s)] = Z\left[\frac{1 - e^{-Ts}}{s} \cdot H_1(s)\right]$$

$$= (1 - z^{-1})\, Z\left[\frac{1}{s} \cdot H_1(s)\right] = \frac{K_1 z^{-1}}{1 - z^{-1}} + A_1 F_1(z) + B_1 F_2(z) z^{-d1},$$

$$F_1(z) = \frac{g_1(z) + g_2(z)}{g_3(z)}, \quad F_2(z) = \frac{h_1(z) + h_2(z)}{h_3(z)}$$

$$g_1(z) = [1 - (1 + a_1 T)\exp(-a_1 T)]z^{-1}$$

$$g_2(z) = [\exp(-2a_1 T) - (1 - a_1 T)\exp(-a_1 T)]z^{-2}$$

Table 1. Constants of Open Loop Transfer Functions(P=Power in %)

1. $H_1(s)$		3. $H_3(s)$	
$K_1=1.11\times10^{-4}$		$A_3=1.17\times10^{-5}$	
$A_1=-0.0244\ e^{-0.1894}\ P-0.0042,$	$P\le15$	$P^3-6.3\times10^{-4}\ P^2+0.01\ P+0.022,$	$P\le25$
$=-0.0237\ e^{-0.1235}\ P-0.0019$	$P>15$	$=0.071-0.0004\ (P-25)$	$P>25$
$B_1=0.0115\ e^{-0.2279}\ P+0.0012,$	$P\le15$	$B_3=2.24\times10^{-4}$	
$=0.0193\ e^{-0.2010}\ P+0.0007$	$P>15$	$P^3+0.00456,$	$P\le5$
$a_1=0.011\ P-0.015,$	$P\le15$	$=3.25\times10^{-5}\ P^2-2.64\times10^{-4}\ P+0.0062$	
$=0.0067\ P+0.05$			$5<P\le20$
$d_1=477\ e^{-0.2687}\ P+38,$	$P\le15$	$=4.92\times10^{-4}\ P+0.00275$	$P>20$
$=231\ e^{-0.1564}\ P+24$	$P>15$	$a_3=0.0195\ P+0.0846,$	$P\le10$
2. $H^2(s)$		$=0.0107\ P+0.1725,$	$10<P\le15$
$K_2=-K_1$		$=0.0082\ P+0.21,$	$15<P\le20$
$A^2=0.0388\ r^{-0.2006}\ P+0.0118,$	$P\le15$	$=0.0125\ P+0.125,$	$P>20$
$=0.0217\ e-0.0142\ e^{-0.2136\ P},$	$P>20$	$b_3=a_3/10$	
$B_2=0.0003-0.0142\ r^{-0.2136\ P},$	$P\le20$	$c_3=0.001\ P,$	$P\le5$
$=0.0$	$P>20$	$=0.399\ P-1.99,$	$5<P\le10$
$a_2=0.0109-0.1221\ e^{-0.0736\ P},$	$P\le20$	$=2.0$	$P>10$
$=0.0805\ P-0.0019$	$P<20$	4. $H_4(s)$	
$b_2=0.022-0.0004\ P,$	$P\le5$	$A_4=4.43\times10^{-4}\ e^{0.0348\ P}$	
$=0.017+0.0013\ P-0.00014\ P^2$	$P>5$	$a_4=\zeta\omega_n$	
$d_2=112-6\ P$		$\omega_n=(\pi/t_p)(1-\zeta^2)^{-0.5}$	
		$t_p=195\ e^{-0.16\ P}+22$	
		$\zeta=0.535\ e^{-0.16\ P},$	≤15
		$=0.172$	$P>15$

$$g_3(z) = 1 - 2\exp(-a_1T)z^{-1} + \exp(-2a_1T)z^{-2}$$
$$h_1(z) = [1-(1+b_1T)\exp(-b_1T)]z^{-1}$$
$$h_2(z) = [\exp(-2b_1T)-(1-b_1T)\exp(-b_1T)]z^{-2}$$
$$h_3(z) = 1 - 2\exp(-b_1T)z^{-1} + \exp(-2b_1T)z^{-2} \quad (5)$$

and the other transfer functions in z domain could be obtained in the same way.

As shown in Eq.(5), the digital transfer function depends on the sampling period T. To evaluate the effect of sampling time on the system responses, four cases with T=1, 2, 4 and 10 seconds are investigated. It is found that the open systems defined by Eqs.(1) through (4) are insensitive to the sampling period, that is, the responses of the z–transformed functions are almost the same for the various sampling intervals. This characteristic could be easily understood by a Fourier transformation [8]. A Fourier transformation shows that the natural frequency, or speed, of the system is so slow that the problems arising from digitalizing, such as a signal aliasing, do not occur unless an unusually long sampling period is applied.

In general, the process control is of slow dynamics and thus has large time constants in contrast with the electro–signal dynamics. It is usual practice to take the sampling frequency 10 to 20 times faster than the fastest component of the system. As a rule of thumb, the process sampling period is about 10 to 30 seconds for the temperature control, 1 to 5 seconds for the pressure control, and 1 to 10 seconds for the liquid level control system [9]. The shorter sampling period is desirable, as far as the engineering situation permits, and is fixed as one second in this study. This is to avoid noise frequencies similar to those of the system which might cause a d–c error even if the Nyquist frequency criterion were satisfied.

3. Digital Control Schemes

Figure 2(a) shows the digital control system model equivalent to the three–element control system [10] commonly applied in current nuclear plants. The steam generator is included as a process plant in this model. Samplers and holders are introduced and analog controllers are replaced by digital controllers.

During transient, the steam flow rate change $\Delta W_s(t)$, primary coolant temperature change $\Delta T_p(t)$, feedwater temperature change $\Delta T_{fw}(t)$, as well as the feedwater flow rate change $\Delta W_f(t)$ are input to the process plant. Figure 2(b) is the block diagram of Figure 2(a) expressed in s domain. The level variation is

$$\Delta L^*(s) = \frac{1}{C^*(s)}\Big\{\Delta W_s^*(s)[G_1^*(s)J_1^*(s) + J_2^*(s) + D^*(s)G_1^*(s)J_2^*(s)] + \Delta T_p^*(s)[J_3^*(s) + D^*(s)G_1^*(s)J_3^*(s)] + \Delta T_{fw}^*(s)[J_4^*(s) + D^*(s)G_1^*(s)G_4^*(s)]\Big\} \quad (6)$$

where

$$C^*(s) = 1 + D^*(s)G_1^*(s) + D^*(s)G_1^*(s)G_2^*(s)J_1^*(s)$$
$$J_i(s) = D(s)H_i(s),\ i = 1,\ 2,\ 3,\ 4$$
$$D(s) = (1 - e^{-Ts})/s$$

$G_1(s)$ and $G_2(s)$ are controllers.

The starred functions above have taken digital processing into account and could directly be expressed in the z domain equations.

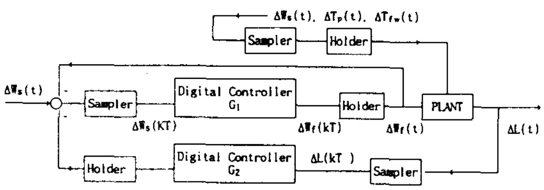

Fig. 2a. Digitalized 3 Element Water Level Control System

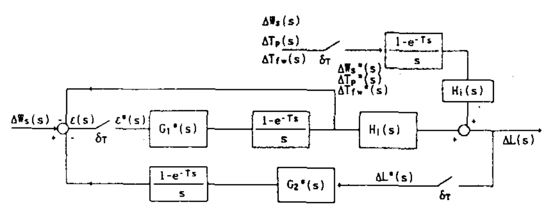

Fig. 2b. Block Diagram of Digitalized 3 Element Control

$$\Delta L(z) = \frac{1}{C(z)}\Big[\Delta W_s(z)[G_1(z)J_1(z) + J_2(z) + G_1(z)J_2(z)] + \Delta T_p(z)[J_3(z) + G_1(z)J_3(z)] + \Delta T_{fw}(z)[J_4(z) + G_1(z)J_4(z)]\Big] \quad (7)$$

where

$$C(z) = 1 + G_1(z) + G_1(z)G_2(z)J_1(z)$$

The first term of Eq.(7) indicates the level variation caused by steam and feedwater flow rate changes and the second and third terms by coolant temperature and feedwater temperature changes respectively.

The characteristic equation of the system is $C(z)$ and is determined by $J_1(z)$. But $J_1(z)$ is related to $H_1(s)$ which includes the delay term. The delay term can be approximated by a series expansion developed by Padè[11]. However the series is too long to be approximated and results in the system order increase. Hence $H_1(s)$ is replaced by one taken from Reference [7], which is given below.

$$H_1(s) = \frac{K_1}{s} + A_S \frac{\omega_n^2}{s^2 + 2\, a_S \cdot s + \omega_n^2} \quad (8)$$

where

$$A_S = -\,0.01268 \cdot \exp[-\,0.0954\ P] + 0.001$$
$$\zeta = 0.1985 \cdot \exp[0.03\ P]$$
$$t_p = 317.7 \cdot \exp[-\,0.1764\ P] + 22$$
$$a_S = \zeta\,\omega_n, \quad \omega_n = (\pi / t_p)\,(1 - \zeta^2)^{-0.5}$$

Among various problems in digitalizing a given analog system, the white noise resulting from coefficient bit errors gives rise to instability of the system. This gets more conspicuous with the increase of system order[12]. As an example, under the initial power condition of 12%, the characteristic equation of the system with $G_1(s)=1$ (neglecting long term oscillation), and $G_2(s)=50(1+1/200s)$, is

$$C(z) = (1.9997 - 7.8971\, z^{-1} + 11.7015\, z^{-2} - 7.7105\, z^{-3} + 1.9064\, z^{-4})/[(1 - z^{-1})^2 \times (1 - 1.9513\, z^{-1} + 0.9560\, z^{-2})] \quad (9)$$

and substituting this into Eq.(7) yields

$$\Delta L(z) = [f(z)\ (1 - z^{-1})]/[g(z)\ (1.9997 - 7.8971\, z^{-1} + 11.7015\, z^{-2} - 7.7105\, z^{-3} + 1.9064\, z^{-4})] \quad (10)$$

If the real values of the denominator coefficients were exactly the same as those shown, the pole-zero cancellation could be possible. But in the process of machine calculation, the coefficient values are different from those above by digital round-off errors and the pole-zero cancellation will not be guaranteed[13],[14]. In this situation, the zero of 1 causes the system instabilty. Moreover, for the case in which poles are located in the vicinity of ± 1, poles found by means of common numerical handling procedures, which always contain the intrinsic errors, may bring about inaccurate results.

To eliminate these difficulties two methods could be considered. One is decreasing the system order and the other is cancelling similar poles and zeros. But in the latter, the exact values of poles and zeros should be found first and the cancellation requires an engineering decision.

With regard to converting the analog system to Eq.(10), the step invariance method is used for the first order s equations and the bilinear transformation for higher order s equations[15]. Although the bilinear transformation causes the output delay by one step of calculation, it is easier to use for high order equations than the step invariance method. And since the frequency of the system under consideration is low, no frequency folding occurs even without prewarping[16].

4. Two-Element Control Schemes

The control scheme in Figure 2 may result in numerical instabilities due to its high system order. For the system to be more practical, the constants of the controller should be determined automatically by adapting to the power. This can be established more easily with low order systems or with a lesser number of controllers. Furthermore, knowledge of the process defined by Eqs.(1) through (4) and (8) permits the exclusion of feedwater feedback loop which is not reliable at low power because of the measuring uncertainty. Feedback loop elimination, of course, affects system stability but it can be compensated by selecting proper controllers.

One of the major differences between an analog controller and a digital controller is that the digital controller includes the hold circuit which causes a phase lag and therefore reduces the stability margin. Thus the hold equivalent of

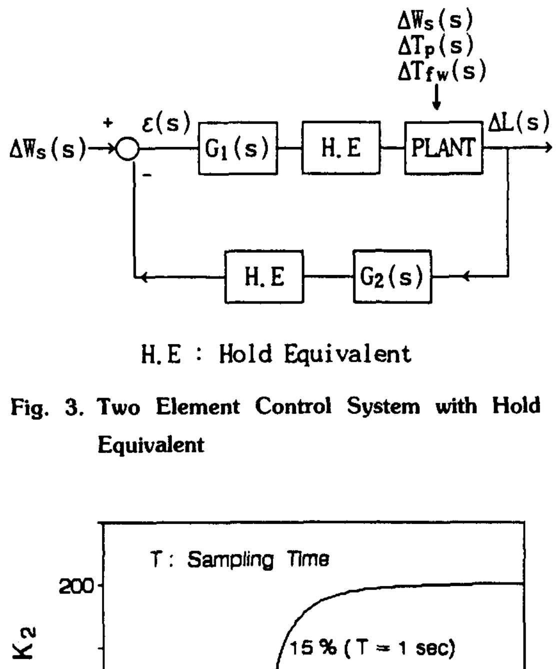

Fig. 3. Two Element Control System with Hold Equivalent

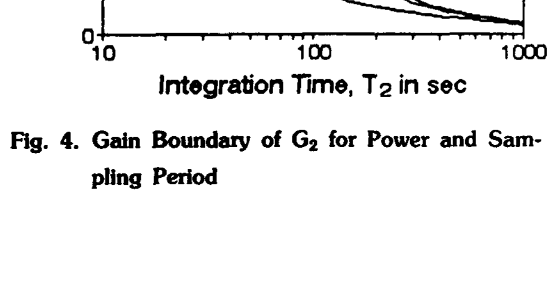

Fig. 4. Gain Boundary of G_2 for Power and Sampling Period

$(1-e^{-Ts})/s \cong T/(Ts/2+1)$ is introduced in anticipation of the conversion from an analog controller to a digital controller. This is described in Figure 3.

When $G_1(s)$ and $G_2(s)$ are PI controllers, the overall system is of sixth order with non-minimum phase. The gain (K_2) of G_2 which makes the system stable depends on the integration time constant T_2 and has both upper and lower limits. Figure 4 shows the boundary of constants of G_2 for the stability with $G_1(s)=1+1/400s$. Two cases of the initial power 5% and 15% are compared each other. For 5% power, sampling periods of 1 and 10 seconds are considered.

As shown in the figure, the stable region reduces with decreasing power. This again indicates the difficulty of operation at low power level. Although the open loop transfer function for each input parameter is insensitive to the sampling period, the overall closed loop transfer function is affected by the sampling period because of the addition of a lag circuit.

Figure 5 shows the stability boundary conditions for different integration time constants (T_1) of controller G_1 at 15% power. The function of an integrator is to decrease the steady state error but it also reduces the system damping to result in instability. In addition, a major function of the controller G_1 is to eliminate long term natural oscillation [10] and during rapid transient its effect is negligible. For these reasons the controller G_1 could be dropped and then the system order decreases to five. For the case in which the system order is odd, the system becomes of minimum phase and the stability boundary has an upper limit only. This leads to easier control operation.

With the absence of G_1, Figure 6 shows the relation between the two control constants, K_2 and T_2. As shown in the figure, the limit of the gain K_2 becomes smaller as the power decreases and, for a given power, it increases with the integration time constant.

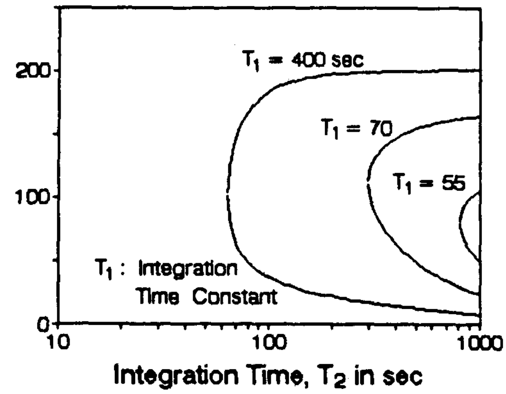

Fig. 5. Gain Boundary of G_2 for T_1

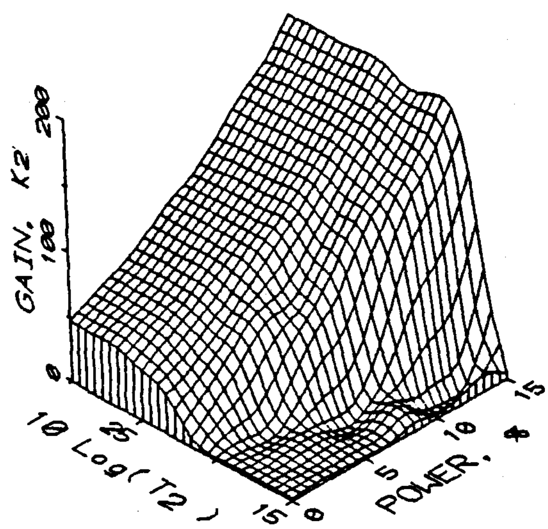

Fig. 6. Gain Boundary of G_2 for Power and Integration Time

Once the boundary of the constants for keeping the system stable is found, it is necessary to determine the exact values which can yield the most desirable system responses. The system should reserve sufficient stability margins and at the same time should satisfy control specifications such as response speed and steady state error.

The phase margin increases with both the gain and integration time but is more sensitive to the latter. Since a larger phase margin causes steady state errors, although preferrable in light of stability, various output responses are compared and 30 degrees of phase margin is chosen in this study. The gain margin is determined to be 3 dB which corresponds to the band limit.

Figure 7 is a Bode diagram by which the constants of controller G_2 are determined for the case of 5% initial power and sampling period of 1 second. It has a gain margin of 3 dB at $\omega=0.013$ rad/sec and phase margin of 31 degrees at $\omega=0.008$ rad/sec using constants of $K_2=58$ and $T_2=400$. With a fixed sampling period of 1 second, the gain and the integration time constant of controller G_2 can be expressed in terms of initial power as in Eq.(11) below. In this case the system retains the same margin values for all power levels including zero power.

$$K_2 = 32.55 + 3.96\,P + 0.212\,P^2,$$
$$T_2 = 641.3 - 60.0\,P + 2.1\,P^2 \qquad (11)$$

The equations above define the digital PI controller of the two-element system and satisfy the necessary control requirements.

Figure 8 shows the level response for the case in which power increases from 5% to 10%. The input conditions are such that the steam flow rate is increasing lineary at the rate of 0.273 kg/sec from t=10 to 70 seconds and the primary coolant temperature is also increasing linearly by 0.03℃ from t=25 to 70 seconds, and by 0.026℃ from t=70 to 80 seconds. There is no feedwater temperature change in the range of 5 to 10% power.

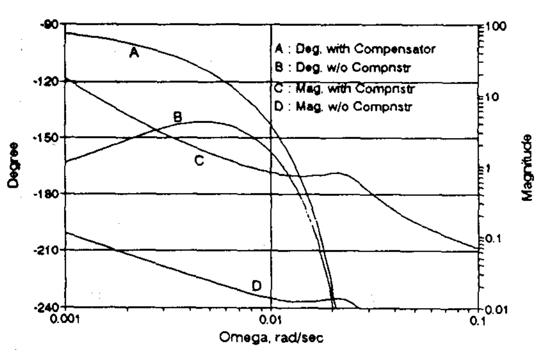

Fig. 7. Bode Diagram for Determining K_2 and T_2

Curve A of Figure 8 is the level variation obtained by the two-element digital control system with the PI controller whose constants are determined by Eq.(11). The equation of the response is of fifth order. It is decomposed into the cascaded form of first and second order IIR filters to avoid high order coefficient errors. And the closed system is rearranged into an open loop form for the application of the DSPlay code[17]. Curve B of the same figure is the result calculated by the two-element analog system which is equivalent to the digital system of Curve A.

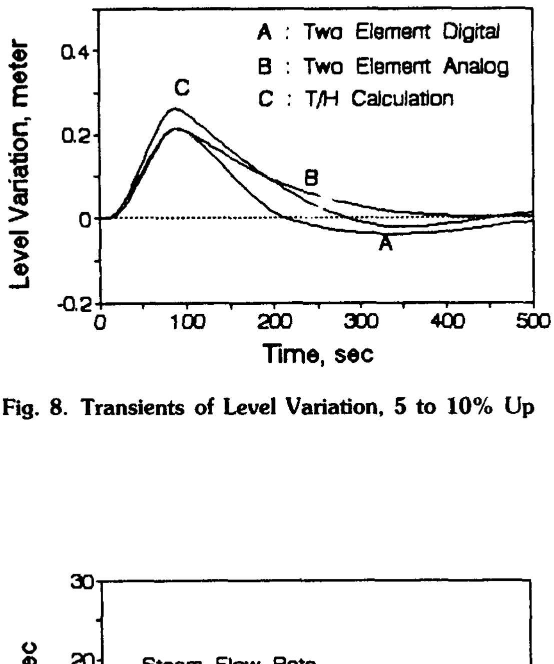

Fig. 8. Transients of Level Variation, 5 to 10% Up

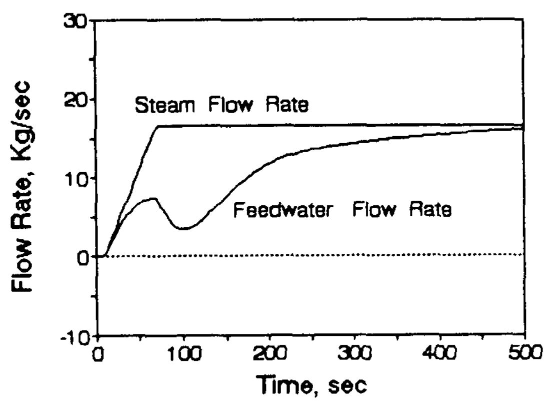

Fig. 9. Transients of Flow Rate Variation, 5 to 10% Up, Case A of Fig. 8.

The level response of Curve C is obtained from the thermal hydraulic model of the steam generator. In Figure 3, the relation between the error (ϵ) and the feedwater flow rate change can be expressed in a difference equation. The variation of feedwater flow rate is determined first from this equation. Then it is input to the thermal hydraulic model of the steam generator to calculate the level variation. In contrast with this thermal hydraulic calculation of Curve C, Curves A and B are obtained by simply inverting the z or s equations since the steam generator is included in the transfer function.

The response of the digital system (A) shows a similar behavior to that of the analog system (B). Particularly the peak values are the same in each case (21 cm at 88 sec). The speed of the digital system is somewhat faster than that of the analog system and the steady state error is larger than that of the analog system.

Comparing the response of the digital system (A) to that of the thermal hydraulic calculation (C), the peak value of Curve A is less than that of Curve C (26 cm at 88 sec). The speed of Curve A is faster than that of Curve C but the steady state error is larger than that of Curve C. The steady state error of the digital system can be reduced by decreasing the integration time constant, at the expense of decreasing the phase margin.

Figure 9 shows the dynamics of the feed water flow rate. As shown in the figure, the feedwater flow rate increases initially and then decreases to compensate for the increasing level. The rate of change of the feedwater flow rate is related to the feedwater valve motion. A rapid valve motion may result in mecahnical problems such as valve seat erosion. This imposes another limitation on the gain. If the rate of change of the feedwater flow rate were too large to be followed up by the mechanical motion of the valve, the gain should be decreased.

5. Conclusion

The relations between various inputs to the steam generator and the level have been identified by making use of the thermal hydraulic model of the steam generator and described in the form of open loop transfer functions. It has been found that since the system is of slow dynamics, the sampling period commonly adopted in process controls could be applied to the system under consideration.

The three-element level control system has been investigated by employing the developed transfer functions of each input to the level. But because of the high order of the system, it is vulnerable to numerical errors particularly when the poles and zeros are located in the neighborhood of ± 1. Even small errors might give rise to instability though the system is, in reality, stable. In addition, the feedwater feedback is not reliable because of the flow measurement uncertainty at low power.

On account of these problems of unreliability and numerical unstableness, a two-element control system has been proposed. Even though a feedback loop is dropped from the system, the controller which maintains system stability could still be designed since the process plant has been identified. By introducing a lag circuit in advance to compensate for the effect of digitalization, a digital PI controller has been designed whose constants are determined by initial power.

This digital controller makes the system retain the same gain and phase margins over the entire power range including zero power. Since the digital controller is defined by power only, it would be simple to operate. And the output of the digital system shows a good conformity with that of the analog system.

However, there are several limitations in this study. First of all, the plant identification in this study is made by a specific type of input. In actual, the input to the steam generator is diverse and the plant should reflect this diversity. Another is the feedwater valve. An ideal valve is assumed in this study but the actuator speed as well as the valve hysteresis will present non-linearity which should be included in the control system.

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References

1. R.E. Uhrig, "Opportunities for Automation and Control of the Next Generation of Nuclear Power Plants," *Nucl. Tech.*, **88**, 157–158 (1989)
2. U.C. Lee et al., "Study on the Development of Integrated Digital Control System," CARR/AI&C-9201, p.19, CARR (1992)
3. K.J. Åström et al., *Computer Controlled Systems*, p.14, Prentice Hall (1984)
4. W.H. Stromayor, *Dynamic Modeling of Vertical U-Tuve Steam Generator for Operational Safety Systems*, Ph. D. Thesis, MIT (1982)
5. J.I. Choi, *Non-Linear Digital Control for Steam Generator System in PWR*, Ph. D. Thesis, MIT (1987)
6. Y.J. Lee, U.C. Lee, "Steam Generator Water Level Control by Control Scheme of Predictor," *Procd. of the 6th KAIF*/KNS Annual Conference, 701–704, KNS (1991)
7. Y.J. Lee, "Water Level Control of Nuclear Plant Steam Generator," *Trans. on KSME J.*, 16, 753–764 (1992)
8. E.O. Brigham, *The Fast Fourier Transformation and Its Application*, p.145–148, Prentice Hall (1988)
9. K. Ogata, *Discrete Time Control Systems*, p.207, Prentice Hall (1987)
10. L.E. Engelhardt et al., "Setpoint Study for

Kori Nuclear Units 5 & 6," p.2–21, Westinghouse (1983)

11. G.F. Franklin et al., *Feedback Control of Dynamic Systems*, p.183, Addison Wesley (1986)
12. S.D. Sterns et al., *Signal Processing Algorithms*, p.92, Prentice Hall (1988)
13. D.M. Young et al., *A Survey of Numerical Mathematics*, p.70–74, Addison Wesley (1972)
14. S. Wolfran, *Mathematica*, p.692, Addison Wesley (1991)
15. K.J. Åström et al., *Computer Controlled Systems*, p.176, Prentice Hall (1984)
16. *ibid.*, p.177
17. DSPlay(Ed.) – The Computer Program for Digital Signal Processing, Burr–Brown Co. (1989)