Study on the Automatization of the Steam Generator Water Level at Low Power

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저출력 증기발생기 수위조절의 자동화

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적 요

원자력 발전소의 증기발생기는 열수력학적 특성에 의하여 저출력에서 수위의 조절이 매우 어려우며, 가동시와 같은 저출력에서 원자로 강제정지의 큰 원인이 되고 있어 경제성 및 안전성에 영향을 미치고 있다. 본고에서는 강제정지 감소 방안의 일환으로 수위 제어의 자동화 영역을 저출력에까지 확장하였으며, 이를 위해 우선 증기발생기의 모델을 수정하여 주요인자에 대한 증기발생기 수위의 거동을 파악하였다. 이들 열수력학적 거동을 전달함수형태로 근사시킨후 전체 제어 시스템의 안정도 및 제어특성을 살폈으며, 제어기의 상수를 출력별로 조절함으로써 자동화 영역이 저출력까지 확장될 수 있음을 보였다.

Introduction

The water level control of the steam generator in a nuclear power plant is difficult to control at low power because of its reverse directional response to feedwater control. The main reason of this behavior is the intrinsic thermal-hydraulic properties of the steam generator which are well known as swell and shrink phenomena. These phenomena are common to all power plants and become more salient as plant power decreases. The failure of the water control causes reactor trips, most of which are spurious at low power. These spurious trips are not desirable with respect to both the plant availability as well as safety. Up to now various statistics (Ku, et al, 1987), (Chao, et al, 1985) show that the feedwater control system including steam generator is the major cause of reactor trips (39 to 44% of all reactor trips), and the detail root causes analysis shows that about 10 to 20 % of all trips are solely by shrink and swell. The present art of the level control at low power is the operator's manual control and above a certain power level the manual mode is switched to automatic mode. But this method may lead to other problems of human error. Therefore it is the most desirable way to extend the range of automatic control into the low power as far as possible to eliminate operator's interface with the plant. A new

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control system is proposed in this paper for the automatic control of steam generator water level without interrupting stability and still with proper control characteristics. This control scheme, named off-line guider, is developed by the use of thermal-hydraulic characteristics of steam generator and responses to key parameters are expressed in the form of transfer functions. With these tranfer functions known and by selecting proper compositions and control constants, the control scheme for automatic control can be defined.

Thermal-Hydraulic Modeling of Steam Generator

To fully understand the thermal-hydraulic properties including the shrink and swell phenomena, a sound model of steam generator is necessary. In this papar, the model of Stromayor (1982) and Choi (1987) as shown in Figure 1 is used with two major modifications. The shrink and swell phenomena is directly related to downcomer flow rate which is calculated by driving forces. At low power, the pressure difference between the tube region and downcomer region is so small that the downcomer flow rate becomes unstable and at the extreme case the so called manometer phenomenon occurs. Further since the thermal-hydraulic condition of a steam generator depends on the energy input to steam generator, more accurate estimation of heat transfer rate from primary coolant to steam generator is required. With respect to these, two modifications are made to the momentum equations and to the heat transfer calculations.

1) Mometum equations

The momentum equations are functions of flow path geometry and other numerous factors as well. The model mentioned above assumed the constant geometry but in reality, the flow path geometry becomes different depending on the position of water level. Accordingly the momentum calculational procedure is modified to be divided into three cases in this paper. The first case is when the water level is in the 'head' of steam generator. The forces induced by each junction flow (see Figure 1) are calculated and summarized as in Table 1. It is to be noted that all the summation of numerator in the momentum inertia is equal to the length of the total flow loop. The second is when the water level is in the 'slope' region of downcomer

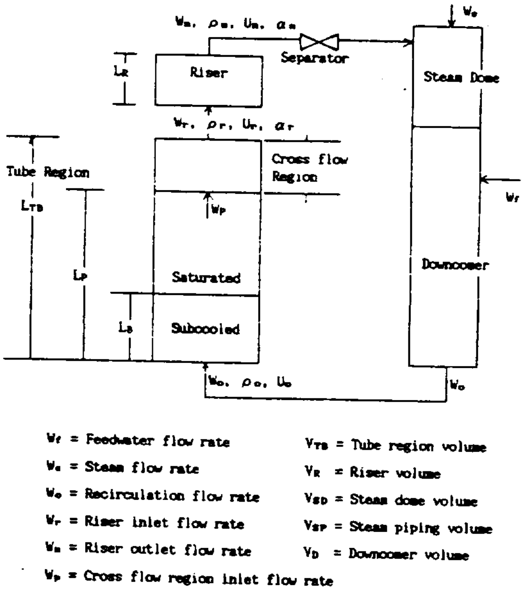

Figure 1. Thermal-hydraulic model of steam generator

Table 1. Forces by each flow

$F(W_o)$	$\frac{\lvert W_o\rvert W_o}{2\rho_o}\cdot\Big[f_1\left(\frac{W_o\cdot D_{HD}}{\mu_o A_D}\right)\cdot\frac{L_D}{D_{HW}\cdot A_D^2}+f_2\left(\frac{W_o\cdot D_{HTB}}{\mu_o A_{TB}}\right)\cdot\frac{(L_p/2)}{D_{HTB}\cdot A_{TB}^2}$ $+f_3\left(\frac{W_o\cdot D_{HW}}{\mu_o A_{ew}}\right)\cdot\frac{(L_w-L_D-ZL_3)}{D_{HW}\cdot A_D^2}+f_4\left(\frac{W_o\cdot D_{HM}}{\mu_o A_M}\right)\cdot\frac{ZL_3}{D_{HM}\cdot A_M^2}\Big]$ $+\frac{W_o^2}{2\rho_o}\cdot\left(\frac{K_{SD}}{A_M^2}+\frac{K_D}{A_D^2}-\frac{1}{A_{TB}^2}\right)$
$F(W_p)$	$\frac{\lvert W_p\rvert W_p}{2\rho_\ell}\cdot\left[f_5\left(\frac{W_p\cdot D_{HTB}}{\mu_\ell A_{TB}}\right)\cdot\frac{\left(\frac{L_{TB}}{2}\right)}{D_{HTB}\cdot A_{TB}^2}+\frac{K_c}{A_{TB}^2}\right]\cdot\Phi^2{}_{lo}\left(X_p,\frac{\lvert W_p\rvert}{A_{TB}}\right)$
$F(W_r)$	$\frac{\lvert W_r\rvert W_r}{2\rho_\ell}\cdot\Big[f_6\left(\frac{W_r\cdot D_{HTB}}{\mu_\ell A_{TB}}\right)\frac{\left(\frac{L_{TB}-L_p}{2}\right)}{D_{HTB}\cdot A_{TB}^2}\cdot\Phi^2{}_{lo}\left(X_r,\frac{\lvert W_r\rvert}{A_{TB}}\right)$ $+f_7\left(\frac{W_r\cdot D_{HR}}{\mu_\ell A_R}\right)\cdot\frac{\left(\frac{L_R}{2}\right)}{D_{HR}\cdot A_R^2}\cdot\Phi^2{}_{lo}\left(X_r,\frac{\lvert W_r\rvert}{A_R}\right)\Big]$ $+\frac{\lvert W_r\rvert W_r}{2\rho_r}\cdot\left(\frac{K_c}{A_R^2}\right)\cdot\Phi^2{}_{lo}\left(X_r,\frac{\lvert W_r\rvert}{A_{TB}}\right)+\frac{W_r^2}{2\rho_r}\left(\frac{1}{A_{TB}^2}-\frac{1}{A_R^2}\right)$
$F(W_n)$	$\frac{\lvert W_n\rvert W_n}{2\rho_n}\cdot\left[f_8\left(\frac{W_r\cdot D_{HR}}{\mu_\ell A_R}\right)\cdot\frac{\left(\frac{L_R}{2}\right)}{D_{HR}\cdot A_R^2}\cdot\Phi^2{}_{lo}\left(X_n,\frac{\lvert W_n\rvert}{A_R}\right)\right]$ $+\frac{W_n^2}{2\rho_n A_R^2}(1+K_{sep})$
gravitational force	$g\cdot\left[L_{TB}\cdot\left(\frac{M_{TB}}{V_{TB}}\right)+L_R\cdot\left(\frac{M_R}{A_R}\right)-\rho_\ell\cdot L_{sat}-\rho_o\cdot L_{sub}\right]$

where the cross sectional area of the flow, accordingly the momentum inertia varies as level changes. In this case, the force of each junction flow is same as that of the first case except the force by downcomer flow rate, which is as below :

$$F(W_o)=\frac{|W_o|W_o}{2\rho_o}\cdot\Big[f_1\left(\frac{W_o\cdot D_{HD}}{\mu_o A_D}\right)\cdot\frac{L_D}{D_{HW}\cdot A_D^2}+f_2\left(\frac{W_o\cdot D_{HTB}}{\mu_o A_{TB}}\right)\cdot\frac{(L_p/2)}{D_{HTB}\cdot A_{TB'}}+f_4\left(\frac{W_o\cdot D_{HM}}{\mu_o A_M}\right)\cdot\frac{ZL_3}{D_{HM}\cdot A_M^2}\Big]+\frac{W_o^2}{2\rho_o}\cdot\left(\frac{D_D}{A_D^2}-\frac{1}{A_{TB}^2}\right)\cdots\cdots\cdots(1)$$

The last case is when the water level is very low and is in the region of vertical part of the downcomer where the cross sectional area is constant. In this case the force by the downcomer flow rate becomes as Eq. (1) and other forces are equal to the previous case.

$$F(W_o)=\frac{|W_o|W_o}{2\rho_o}\cdot\Big[f_1\left(\frac{W_o\cdot D_{HD}}{\mu_o A_D}\right)\cdot\frac{L_W}{D_{HW}\cdot A_D^2}+f_2\left(\frac{W_o\cdot D_{HTB}}{\mu_o A_{TB}}\right)\cdot\frac{(L_p/2)}{D_{HTB}\cdot A_{TB}^2}\Big]+\frac{W_o^2}{2\rho_o}\cdot\left(\frac{k_D}{A_D^2}-\frac{1}{A_{TB}^2}\right)\cdots\cdots\cdots(2)$$

The comparion of the modified result with the existing model shows the decrease of the downcomer flow rate about 3%, which indicates the more unstable properties of steam generator.

2) Heat transfer model

The existing model of Stromayor and Choi assumed the constant heat transfer rate all through the heat transfer area. But since the tube region consists of two regions of single phase and two phase, the heat tranfer rate is different each other. Particulary at low power, the single phase region is large and it introduces an error to treat the whole region as two phase. Therefore, to represent the heat transfer rate more accurately, different correlations are used for each region. The point of onset of boiling is found first, and with this point as a boundary, Dittus-Boelter is used for single phase region, and Thom's correlation (1964) is applied for two phase region. In Figure 2 of primary heat transfer model, q_1 and q_3 are heat transfer rates of single phase and q_2 is for two phase which are expressed as :

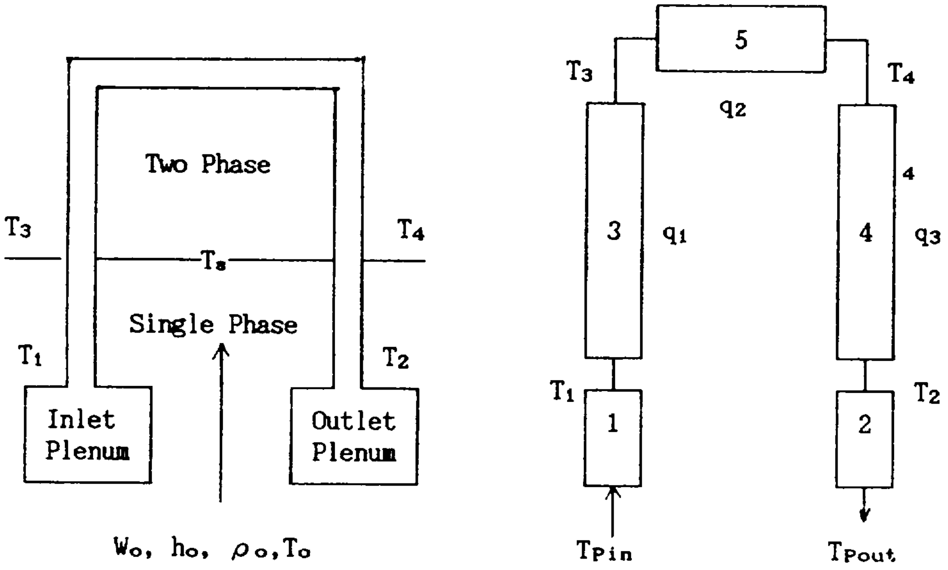

Figure 2. Primary heat transfer model

$$q_1=\frac{\frac{f\cdot A_T}{2}}{\frac{1}{h_{o1}}+\frac{r_o}{k_1}\ln\frac{r_o}{r_i}+\frac{r_o}{r_i}\cdot\frac{1}{h_{i1}}}\cdot\frac{(T_1-T_o)-(T_3-T_s)}{\ln\left[\frac{T_1-T_o}{T_3-T_s}\right]}$$

$$=W\cdot(T_1-T_3)\cdot c_p[p,T,h(T,p)] \cdots\cdots\cdots\cdots(3)$$

$$q_2=\frac{(1-f)\cdot A_T}{\frac{1}{h_{o2}}+\frac{r_o}{k_2}\ln\frac{r_o}{r_i}+\frac{r_o}{r_i}\cdot\frac{1}{h_{i2}}}\cdot\frac{(T_3-T_4)}{\ln\left[\frac{T_3-T_s}{T_4-T_s}\right]}$$

$$=W\cdot(T_3-T_4)\cdot c_p[p,T,h(T,p)] \cdots\cdots\cdots\cdots(4)$$

$$q_3=\frac{\frac{f\cdot A_T}{2}}{\frac{1}{h_{o3}}+\frac{r_o}{k_3}\ln\frac{r_o}{r_i}+\frac{r_o}{r_i}\cdot\frac{1}{h_{i3}}}\cdot\frac{(T_4-T_s)-(T_2-T_o)}{\ln\left[\frac{T_4-T_s}{T_2-T_o}\right]}$$

$$=W\cdot(T_4-T_2)\cdot c_p[p,T,h(T,p)] \cdots\cdots\cdots\cdots(5)$$

where f is the the distance ratio of OSB and A_T is total heat transfer area.

In the above equations, all the properties are functions of temperature and the temperature of each junction can be obtained by establishing the conservation equations of mass and energy for each nodal volume. By introducing the assumption that the rate of change at each junction is same as that of upstream nodal volume, .the temperatures are determined at a ceratin time, and are used for the heat transfer calculation of next time step. The results of the heat transfer modification show the decrease of the system pressure of about 2% below that of existing model, which is as expected since Thom's correlation is sensitive to the system pressure while Dittus-Boelter is not.

In summary, the thermal hydraulic model of the steam generator are expressed in terms of six unknowns. They are internal enegy of downcomer flow, vapor volume, riser inlet and outlet void fraction, system pressure and system flow rate. The last one is again expressed as a function of junction flow rates of Figure 1, and overall model is expressed in the linear equation as below.

$$A \cdot \frac{d}{dt} \underline{\Phi} = B$$

$$B = \mathrm{Col}\,[\overline{W}(h_o - h_r) + Q_B,\ \overline{W}(h_r - h_n),\ \overline{W}(h_n - H_k) - W_s(h_g - H_k),\ W_{fw}(h_{fw} - H_k) - \overline{W}(h_o - H_k),\ W_{fw} - W_s,\ -F] \cdots\cdots\cdots\cdots\cdots (6)$$

where h is enthalpy, and H_k is the enthalpy condition at movable surface at downcomer boundary and Q_B is the total heat transfer rate from primary to secondary.

The elements of matrix A is of 6×6, and are functions of all known variables. By matrix inversion, the vector $\underline{\Phi}$ of which elements are six unknowns is found at next time step.

3. Water Level Control System

The thermal-hydraulic model of the steam generator developed above is applied for various cases. Four(4) parameters of feedwater flow rate, steam flow rate, primary coolant temperature and feedwater temperature are considered as major inputs to the steam generator. By step changing a particular parameter with others fixed, the relation between that parameter and the steam generator level can be analyzed. Figures 3 and 4 show the shrink and swell of level due to feedwater and steam, for an example. To describe the relations between key parameters and the level in the form of transfer function, the regression routine of IMSL(1984) is used and the constants of the transfer function are expressed in terms of initial power of the plant. The transfer functions for each parameter are :

$$H_1(s) = \frac{K_1}{s} - V_{s1} \cdot \frac{\omega_n^2}{s^2 + 2a \cdot s + \omega_n^2} \cdots\cdots\cdots (7)$$

$$H_2(s) = \frac{K_1}{s} - V_{s2} \cdot \frac{0.05}{s^2 + 0.05} \cdots\cdots\cdots (8)$$

$$H_3(s) = [K_2 \cdot \frac{a-b}{(s+a)(s+b)} - K_3 \cdot \frac{c}{s+c} \cdot \exp(-2s) \cdots\cdots\cdots (9)$$

$$H_4(s) = 4.43 \times 10^{-4} \cdot \exp[0.0348 \times \mathrm{power}] \frac{\omega_n^2}{s^2 + \omega_n^2} \cdots\cdots (10)$$

where V_{s1} is the steady state value and K_1, K_2 are proportional gain. And a,b,c are control constants which are functions of initial power.

In the above, $H_1(s)$ is the transfer function of feedwater, $H_2(s)$ is for steam flow rate, $H_3(s)$ is for primary temperature and $H_4(s)$ for feedwater temperature. With these equations

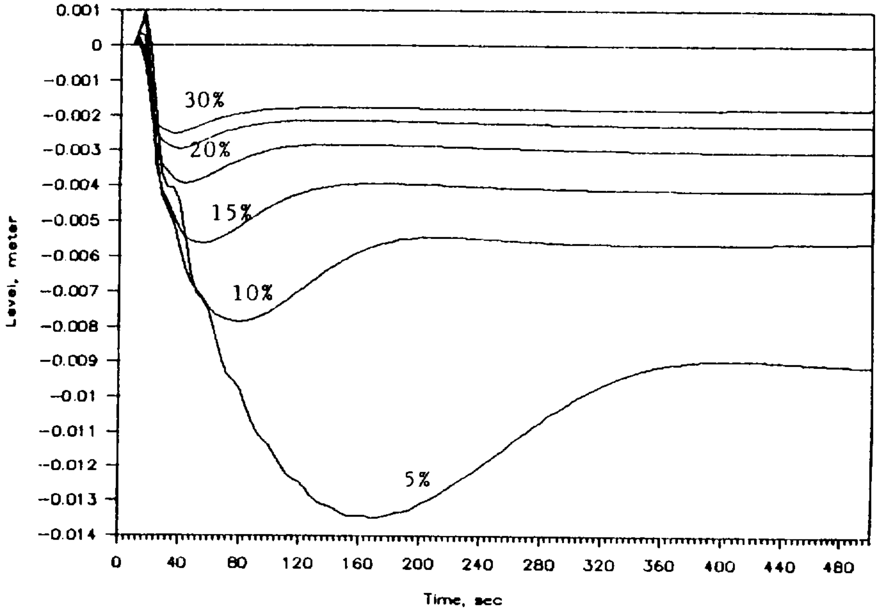

Figure 3. Shrink effect by feedwater (5 to 30 %)

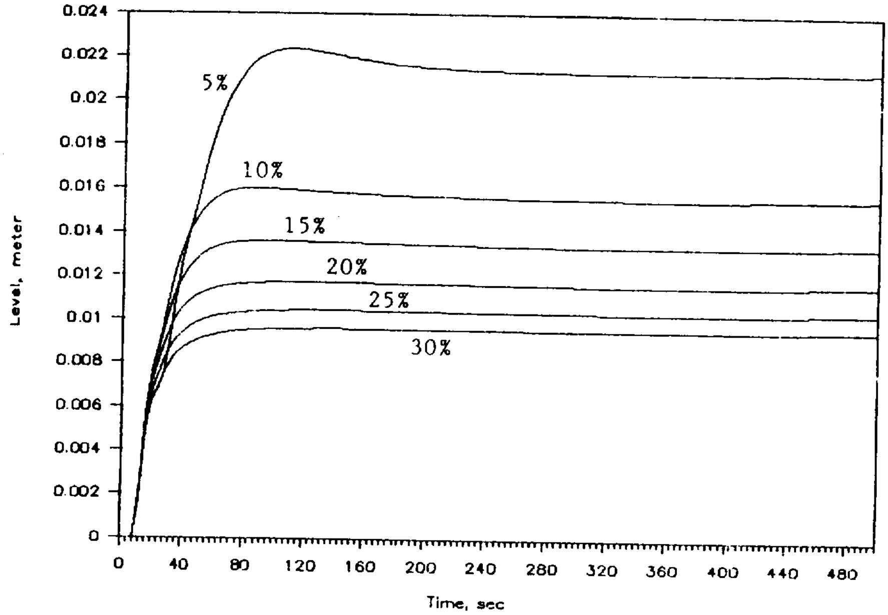

Figure 4. Swelling effect by steam (5 to 30%)

the level at time t is obtaind by inversing Laplacian.

$$\ell_3(t) = L^{-1}(H_1(s) \cdot \Delta W_f(s) + H_2(s) \cdot \Delta W_s(s) + H_3(s) \cdot \Delta T_p + H_1(s) \cdot \Delta T_f(s)) \cdots\cdots\cdots (11)$$

The above equation tells us that the thermal hydraulic model of a steam generator is no more necessary in computing the water level. That is, since the properties of response to each key parameter are known, the steam generator is treated as a control plant which is nothing more than a kind of control component and the level control problem is reduced to the control problem without regard to thermal-hydraulic characteristics of the steam generator. Figure 5 is a typical 3 element level control scheme which consists of two feedback paths. But at low power the measurement of flow are always uncertain and it is meaningless to use this variable as a feedback. Therefore the flow feedback loop is removed. In general, the elimination of a feedback loop out of a control system makes the system unstable, but since the control characteristics of the steam generator are fully known at any power level, the boundary of the controller constants which makes the

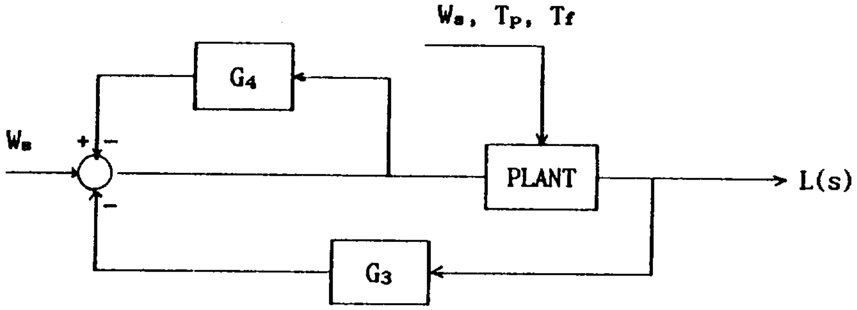

Figure 5. Three(3) element control of water level

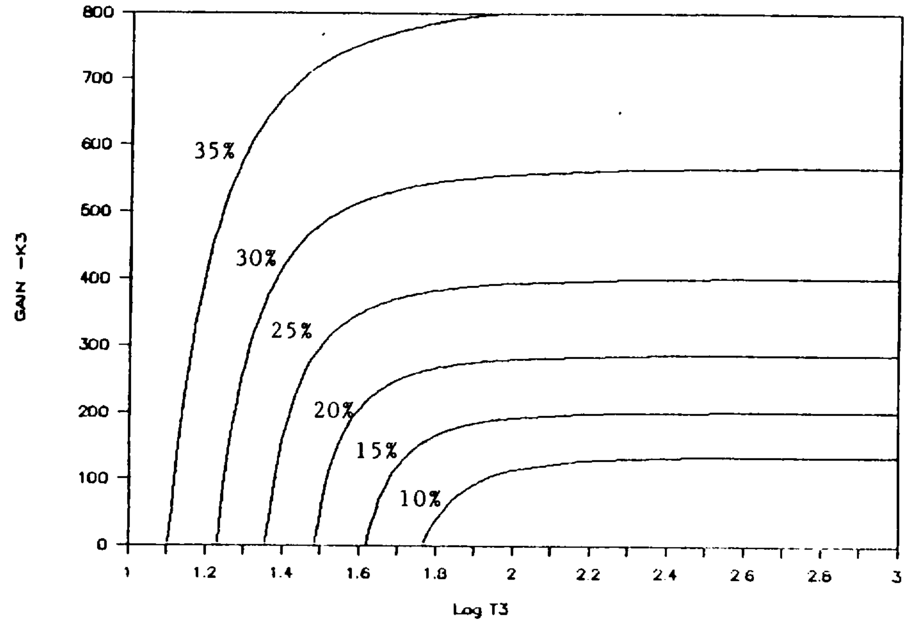

Figure 6. Boundary of gain for system stability, 10 to 35% power

system stable can be defined, though the boundary is limited. Figure 6 shows the boundary of proportional gain and integral reset time of the level feedback controller. As in the figure, the boundary becomes small as power decreases, which means difficult level control at low power as explained before. Still within this boundary, the stability can be maintained together with proper control charateristics. Finally considering that the integrator whose function is to eliminate the steady state error makes the system unstable, the integrator of the level feedback controller is removed, resulting a simple proportional controller. This scheme is named off-line guider. Since only one constant is to be adjusted, eaisier and simpler definition of the system is possible. As its name implies, it can calculate the level without being limited by the time step because the whole system is expressed in anlytical equations. Therefore the water lvel and its corresponding feedwater condition estimated in advance guide an operator what to do for avoiding the water level trips. Figure 7 shows the result of off-line guider applied to the case of power increases from 5 to 10%. As shown in the figure, the level variation is mild, and other control characteristis such as settling time are better than those of existing model of Choi, who uses the compensated level as a feed-back which is calculated by the observer. In addition, when the off-line guider is used together with the thermal-hydraulic model of steam generator as on-line, the results are improved further as compared in Figure 7. The water level converges to the reference level without going to minus range, and

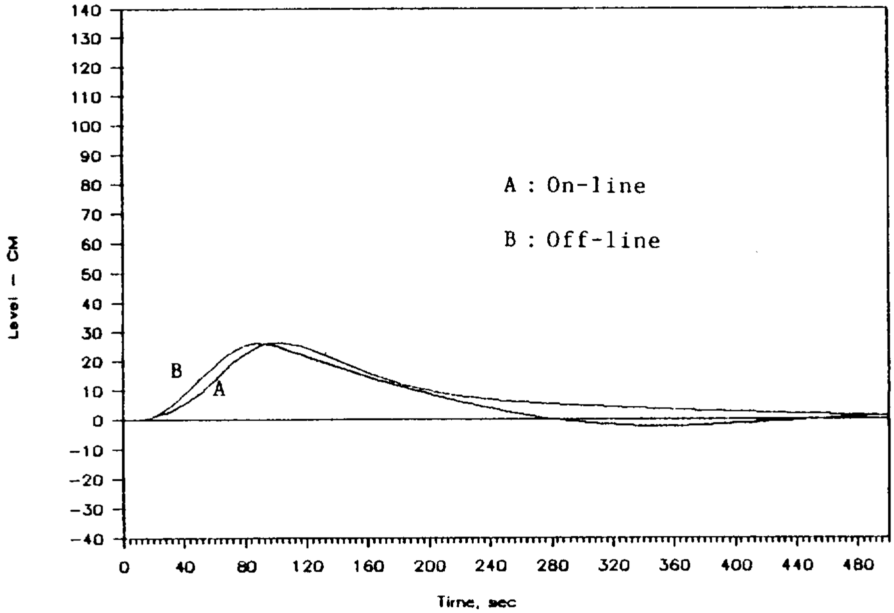

Figure 7. Level variation of power increase from 5% to 10%

overall trends are similar to the results of off-line, which indicates the fact that the off-line guider can be applied on-line with the same scheme and constants.

4. Discussions

The new control scheme proposed in this paper is based on the sound model of steam generator and can be regarded to represent the thermal-hydraulic characteristics of the steam generator more realistically. But the actual behavior of the equipment such as valve and actuator does not follow as required by the calculation of feedwater flow rate. The non-linearity of valve hysteresis and delay time contribute the error to the water level and this non-linearity should be included in the control system to describe the system.

Also the power condition which is represented by the steam flow rate in this scheme and is treated as an input condition should be modified to reflect the reactivity temperature feedback. For this, the nuclear and thermal-hydraulic model of the primary system should be included, and by doing so, the power is to be a state variale which is not necessarily measured, say, the power is no more a input condition. Despite these limitations, the control scheme of off-line guider is a kind of adaptive control in the sense that the control constants varies as power changes (Astrom, 1987), and shows the possibility of extending the automatic control range into the lower power regions.

References

Astrom, K.J. 1987. Adaptive feedback control, Proc. of the IEEE, Vol.75, No.2, 185.

Chao, J. et al. 1985. Scram reduction by relaxing setpoints - an anlysis of C-E PWRs with analog control using RETRAN-02, EPRI NSAC-92, 43-45.

Choi, J.I. 1987. Non-linear digital control for steam generator system in PWR, Ph.D. Thesis, MIT

IMSL Inc. 1984. IMSL Library, Regression analysis, Vol-4.

Ku, J.Y. et al. 1987. Propsed methods for reducing reactor trips, KAERI NP-61, 14-44.

Stromayor, W.H. 1982. Dynamic modeling of vertical U-tube steam generator system in PWR, Ph. D. Thesis, MIT

Thom, J.R.S. 1964. Preditions of pressure drop during forced circulation boiling of water, Int. J. Heat Mass Tranfer, 7, 709-724.