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THE MODEL PREDICTIVE CONTROLLER FOR THE FEEDWATER AND LEVEL CONTROL OF A NUCLEAR STEAM GENERATOR

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Steam generator level control at low power is difficult due to its adverse thermal hydraulic properties, and is usually conducted by an operator. The basic model predictive control (MPC) is similar to the action of an operator in that the operator knows the desired reference trajectory for a finite period of time and takes the necessary control actions needed to ensure the desired trajectory. An MPC is based on a model; the performance as well as the efficiency of the MPC depends heavily on the exactness of the model. In this study, steam generator models that can describe in detail its thermal hydraulic behaviors, particularly at low power, are used in the MPC design. The design scope is divided into two parts. First, the MPC feedwater controller of the feedwater station is determined, and then the MPC level controller for the overall system is designed. Because the dynamic properties of a steam generator change with the power levels, a realistic situation is simulated by changing the transfer functions of the steam generator at every time step. The resulting MPC controller shows good performance.

KEYWORDS : Nuclear Steam Generator, Model Predictive Control, Level Control, Feedwater Control

1. INTRODUCTION

Nuclear steam generators have a number of problems in light of control design. These control problems are directly related to the physical characteristics of the steam generator. The steam generator mechanism is based on the thermal-hydraulic phenomena of heat transfer and fluid dynamics. This makes the mathematical modeling of a thermal-hydraulic system very difficult. There are many intrinsic uncertainties, no matter how exactly it may be modeled. This is mainly due to theoretical assumptions, linearizations, and experimental correlations. Furthermore, the dynamics of the working fluid cause additional uncertainty.

The thermal-hydraulic phenomena of the steam generator produce the shrink and swell effects. These effects are addressed by the control terminology of a non-minimum phase. The control design of a non-minimum phase plant is more difficult than of an unstable plant [1]. The non-minimum phase effect becomes more salient as the power becomes lower, resulting in a higher difficulty in the level control. The control is therefore conducted by an operator at low power, and then is switched to an automatic mode when the steam generator becomes stable with the increase of power.

Many controllers have been developed using various algorithms ranging from the classical PID with variable gains to LQG/LTR (Linear Quadratic Gaussian/Linear Transfer Recovery) [2], to H_∞ robust control, and to μ-synthesis [3]. All of these algorithms are to deal with the uncertainties of the steam generator model. However, it is not easy to make an optimal compromise between the system performance and stability. In addition, the order of the designed controller may be so high that the practical implementation of the controller becomes difficult.

The model predictive control (MPC) method has the potential to be a viable alternative to the steam generator level control system design. Its basic concept is similar to the actions of a human operator; it reflects the behavior whereby he selects the appropriate control actions which he thinks will lead to the best predicted output over some limited time horizon, that is, over some future period. This is the same as the manual operation of a steam generator at low power.

Most control laws do not explicitly consider the future implication of current control actions. To some extent, the future response is only accounted for by the expected closed loop dynamics. The MPC method, on the other hand, explicitly computes the predicted behavior over some horizon and it can therefore restrict the choice of the current proposed input trajectories to those that do not lead to difficulties in the future.

The term MPC does not designate a specific control strategy but rather an ample range of control methods which make explicit use of the process model to obtain the appropriate control signal by minimizing an objective function. These methods lead to controllers which have practically the same structure as conventional controllers and therefore present adequate degrees of freedom [4]. The basic ideas of MPC are: (1) explicit use of a model to predict the process output at future time horizons; (2) calculation of a control sequence minimizing an objective function; and (3) receding strategy, so that at each instant the horizon is displaced towards the future, which involves the application of the first control signal of the sequence calculated at each step.

The MPC has developed considerably over the last two decades, and is regarded as the most general way to pose the process control problem in the time domain. The MPC formulation integrates an optimal control, a stochastic control, a process control with dead time, a multivariable control, and future references when available. Another advantage of the MPC is that because of the finite control horizon used, the constraints and, in general, the nonlinear processes frequently encountered in industry can be handled [5].

In this study, an MPC is applied to the steam generator feedwater and level control system. The performance of the MPC depends on the accuracy of the model. The steam generator model used in this study can take into account the various variables acting on the steam generator. They are: the steam flow rate, feedwater flow rate, primary coolant temperature, and feedwater temperature. The model also takes into account the effects of thermal power changes.

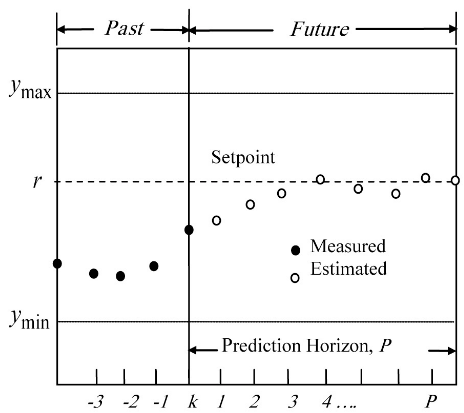
Two MPC controllers have been designed. First, the feedwater station MPC controller was determined. Then the MPC controller for the level control was designed. The constraints arising from the actual operation have been taken into account. And through the simulation it was found that the designed MPC controllers give a good dynamic performance.

2. MPC CONTROL LAW

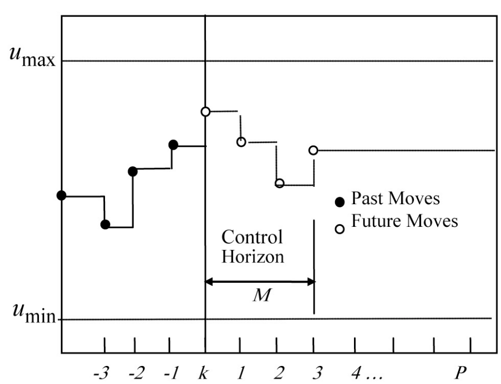
Figure 1 shows the basic idea of MPC [6],[7]. In this simple case, the input trajectory is chosen to obtain the desired plant output at the end of the prediction horizon, namely at time $k+P$, at the required value of $r(k+P)$. There are several input trajectories of $\{\hat{u}(k \mid k), \hat{u}(k+M \mid 1), \ldots, \hat{u}(k+M-1 \mid k)\}$. Once a future input trajectory has been chosen, only the first element of that trajectory is applied as the input signal to the plant, namely, $u(k)=\hat{u}(k \mid k)$, where $u(k)$ denotes the actual signal applied. Then the whole cycle of output measurement, prediction and input trajectory determination is repeated, one sampling period later. Since the prediction horizon remains of the same length as before, but slides along by one sampling interval at each time step, this way of controlling a plant is often called a receding horizon strategy.

Figure 2 describes the overall structure of an MPC system for the case of a SISO (single input single output) system, which can be generalized directly to a MIMO (multi inputs multi outputs) plant.

The main objective is to hold the controlled output ($\bar{y}$) at a reference value, or setpoint (r) by adjusting a manipulated variable u. A model is used to predict the future plant output, based on the past and current values and on the proposed optimal future control actions. These actions are calculated by the MPC controller taking into account the cost functions and constraints. As shown in the figure, the plant has multiple inputs. In addition to the manipulated variable input, u, there may be a measured disturbance, v. The unmeasured disturbance, d, is always present. It is an independent input, not affected by the controller or the plant. It represents all the unknown, unpredictable events.



(a) Prediction Horizon



(b) Input Horizon

Fig. 1. Basic Concept of MPC (a) Prediction Horizon (b) Input Horizon

The effect of the unmeasured disturbance on the controller is through the measured output. A measured disturbance, v, is another independent input. In contrast to d, the controller receives the measured disturbance directly. This allows the controller to immediately compensate for v's impact on $\bar{y}$ rather than waiting until the effect appears in the y measurement.

The determination of $u(k)$ is comprised of two phases, i.e. estimation and optimization. In order to produce the exact input trajectory, the controller needs to know the current state, which includes the true value of the controlled variable, $\bar{y}(k)$, and all the internal variables that influence the future trend of $\bar{y}(k+1)$, … $\bar{y}(k+P)$. In order to accomplish this, the controller uses all of the past and current measurements.

The setpoint values, measured disturbances, and constraints are specified over a finite horizon of future sampling instants, $k+1$, $k+2$, … $k+P$, where is the prediction horizon. These values constitute the cost function. The controller determines M moves of $u(k)$, $u(k+1)$, … $u(k+M-1)$, where M is the control horizon, in such a way that optimizes the cost function.

In Fig. 2, the disturbance is described by:

$$x_d(k+1) = \bar{A}x_d(k) + \bar{B}n_d(k),\qquad d(k) = \bar{C}x_d(k) + \bar{D}n_d(k) \tag{1}$$

,where $n_d(k)$ is a white Gaussian. By neglecting the measurement noise, the model of Fig. 2 can be described by a set of state space equations:

$$\begin{aligned} x(k+1) &= Ax(k) + B_u u(k) + B_v v(k) + B_d d(k) \\ &= Ax(k) + B_u u(k) + B_v v(k) \\ &\quad + B_d\left(\bar{C}x_d(k) + \bar{D}n_d(k)\right) \\ y(k) &= Cx(k) + D_u u(k) + D_v v(k) + D_d\left(\bar{C}x_d(k) + \bar{D}n_d(k)\right) \end{aligned} \tag{2}$$

With the assumption of D_u=0 and by introducing new notations, for simplicity, of

$$\begin{pmatrix} x \\ x_d \end{pmatrix} \to x,\ \begin{pmatrix} A & B_d\bar{C} \\ 0 & \bar{A} \end{pmatrix} \to A,\ \begin{pmatrix} B_u \\ 0 \end{pmatrix} \to B_u,$$

$$\begin{pmatrix} B_v \\ 0 \end{pmatrix} \to B_v,\ \begin{pmatrix} B_d\bar{D} \\ \bar{B} \end{pmatrix} \to B_d,\ \begin{pmatrix} C \\ D_d\bar{C} \end{pmatrix}^T \to C,\ D_d\bar{D} \to D_d,$$

Eq.(2) becomes:

$$\begin{aligned} x(k+1) &= Ax(k) + B_u u(k) + B_v v(k) + B_d n_d(k) \\ y(k) &= Cx(k) + D_v v(k) + D_d n_d(k) \end{aligned} \tag{3}$$

By setting $n_d(i)$=0 for all prediction instants, i, the state variables are obtained as:

$$\begin{aligned} x(i) = x(k+p)\big|_{k=0,\,p=i} &= A^i x(0) + \sum_{h=0}^{i-1} A^h B_u u(-1) \\ &+ \sum_{j=0}^{i-1}\left(\sum_{h=0}^{i-1-j} A^h B_u \Delta u(j)\right) + \sum_{h=0}^{i-1} A^h B_v v(i-1-h) \end{aligned} \tag{4}$$

,with the predicted output of $y(i)=Cx(i)+D_v v(i)$, which gives:

$$\begin{pmatrix} y(1) \\ \vdots \\ y(p) \end{pmatrix} = S_x x(0) + S_{u1}u(-1) + S_u \begin{pmatrix} \Delta u(1) \\ \vdots \\ \Delta u(p-1) \end{pmatrix} + H_v \begin{pmatrix} v(0) \\ \vdots \\ v(p) \end{pmatrix}$$

$$S_x = \begin{pmatrix} CA & CA^2 & \cdots & CA^p \end{pmatrix}^T \in \Re^{pn_y \times n_x},$$

$$S_{u1} = \begin{pmatrix} CB_u & CB_u + CAB_u & \cdots & \sum_{h=0}^{p-1} CA^h B_u \end{pmatrix}^T \in \Re^{pn_y \times n_u},$$

$$S_u = \begin{pmatrix} CB_u & 0 & \cdots & 0 \\ CB_u + CAB_u & CB_u & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ \sum_{h=0}^{p-1} CA^h B_u & \sum_{h=0}^{p-2} CA^h B_u & \cdots & CB_u \end{pmatrix} \in \Re^{pn_y \times pn_u}, \tag{5}$$

$$H_v = \begin{pmatrix} CB_v & D_v & \cdots & 0 \\ CAB_v & CBv & D_v & 0 \\ \vdots & \vdots & \cdots & \vdots \\ CA^{p-1}B_v & CA^{p-2}B_v & \cdots & D_v \end{pmatrix} \in \Re^{pn_y \times (p+1)n_v}$$

The cost function of the MPC plays an important role in the optimization phase, and, accordingly, it is a crucial component that determines the control law of the entire

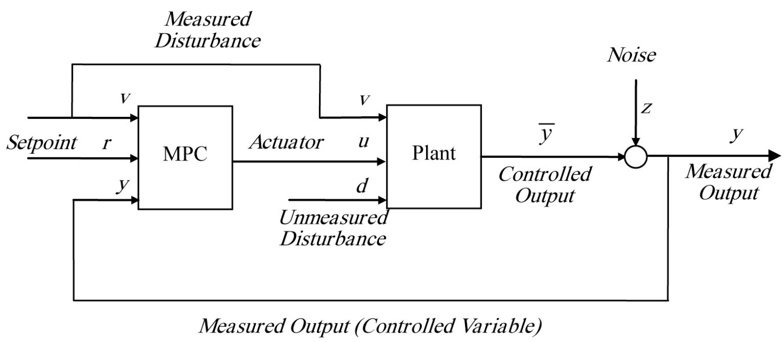


Fig. 2. Structure of MPC

MPC system. In general, the cost function is comprised of the errors between the target trajectory and the predicted outputs, and the errors between the target inputs and predicted inputs. However, in reality, there are constraints on the rate of input change. For example, the control rod speed is restricted in a nuclear reactor, and similarly, all the actuators have limitations on their movements. Therefore, it is more realistic to include the rate of input change in the cost function in addition to the errors of output and input.

The cost function can be set out in various forms, but the typical one is the quadratic function of:

$$J = \left(\begin{bmatrix} u(0) \\ \vdots \\ u(p-1) \end{bmatrix} - \begin{bmatrix} u_{\text{target}}(0) \\ \vdots \\ u_{\text{target}}(p-1) \end{bmatrix} \right)^T W_u^2 \left(\begin{bmatrix} u(0) \\ \vdots \\ u(p-1) \end{bmatrix} - \begin{bmatrix} u_{\text{target}}(0) \\ \vdots \\ u_{\text{target}}(p-1) \end{bmatrix} \right) + \begin{pmatrix} \Delta u(0) \\ \vdots \\ \Delta u(p-1) \end{pmatrix}^T W_{\Delta u}^2 \begin{pmatrix} \Delta u(0) \\ \vdots \\ \Delta u(p-1) \end{pmatrix} + \left(\begin{bmatrix} y(1) \\ \vdots \\ y(p) \end{bmatrix} - \begin{bmatrix} r(1) \\ \vdots \\ r(p) \end{bmatrix} \right)^T W_y^2 \left(\begin{bmatrix} y(1) \\ \vdots \\ y(p) \end{bmatrix} - \begin{bmatrix} r(1) \\ \vdots \\ r(p) \end{bmatrix} \right) \quad (6)$$

, where the weighting matrices are:

$$W_u = diag\left(w_{0,1}^u \; w_{0,2}^u \; \cdots \; w_{0,n_u}^u \; \cdots \; w_{p-1,1}^u \; w_{p-1,1}^u \; \cdots \; w_{p-1,n_u}^u \right)$$

$$W_{\Delta u} = diag\left(w_{0,1}^{\Delta u} \; w_{0,2}^{\Delta u} \; \cdots \; w_{0,n_u}^{\Delta u} \; \cdots \; w_{p-1,1}^{\Delta u} \; w_{p-1,1}^{\Delta u} \; \cdots \; w_{p-1,n_u}^{\Delta u} \right)$$

$$W_y = diag\left(w_{1,1}^y \; w_{1,2}^y \; \cdots \; w_{1,n_y}^y \; \cdots \; w_{p,1}^y \; w_{p,2}^y \; \cdots \; w_{p,n_y}^y \right) \quad (7)$$

Usually, there are lower and upper limits on the predicted outputs, inputs and rates of input change, as laid out in Eq.(8), and these are additional constraints of Eq.(6).

$$\begin{bmatrix} y_{\min}(1) \\ \vdots \\ y_{\min}(p) \\ u_{\min}(0) \\ \vdots \\ u_{\min}(p-1) \\ \Delta u_{\min}(0) \\ \vdots \\ \Delta u_{\min}(p-1) \end{bmatrix} \le \begin{bmatrix} y(1) \\ \vdots \\ y(p) \\ u(0) \\ \vdots \\ u(p-1) \\ \Delta u(0) \\ \vdots \\ \Delta u(p-1) \end{bmatrix} \le \begin{bmatrix} y_{\max}(1) \\ \vdots \\ y_{\max}(p) \\ u_{\max}(0) \\ \vdots \\ u_{\max}(p-1) \\ \Delta u_{\max}(0) \\ \vdots \\ \Delta u_{\max}(p-1) \end{bmatrix} \quad (8)$$

The cost function of Eq.(6) has a Hessian of semi-definite positive, therefore the problem is one of convex optimization [8], from which an analytical solution can be obtained. But with the constraint of Eq.(8), the convexity is not guaranteed, and so the solution could be obtained numerically through the use of a QP (Quadratic Program) [6], [9]. In addition, other optimization algorithms, such as the gradient method, random search method, or enumerative method, could be used [10],[11].

3. MPC CONTROLLER FOR STEAM GENERATOR FEEDWATER AND LEVEL CONTROL

3.1 Steam Generator Feedwater and Level Control System

Figure 3 shows the steam generator feedwater control system. The overall system is a regulating system in which the level variation needs to be kept constant. The steam flow rate change and other feedback signals generate a driving signal that controls the feedwater flow rate in order to keep the level constant. The feedwater station employs 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 the level variation (ΔL). However, noises act on the plant. They are the changes of coolant temperature (ΔT_P) and feedwater temperature (ΔT_F). It should also be noted that the steam flow rate change (ΔW_S) is not only a command signal to the system but also a disturbance to the steam generator. Furthermore, since the properties of the plant change with the power level, the relationships between these inputs and the level need to be characterized.

The steam generator is represented by a set of MIMO (multi input, multi output) transfer functions which reflect all the important thermal hydraulic behaviors of the system [3]. For example, the transfer function between the variations of level and feedwater flow rate is:

$$H_1(s,P) = \frac{\Delta L}{\Delta W_F} = \frac{1.11\times 10^{-4}}{s} + K(P)\frac{\omega_n^2(P)}{s^2 + 2\zeta(P)\omega_n(P)s + \omega_n^2(P)} \quad (9)$$

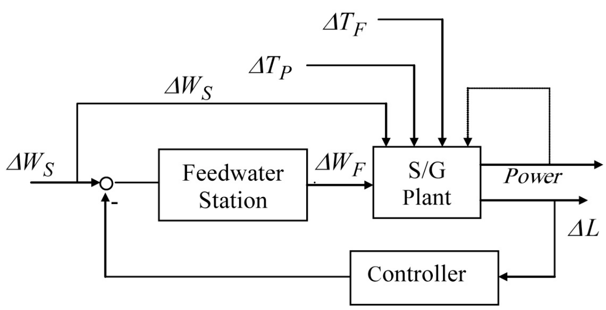


Fig. 3. Schematic of Nuclear Steam Generator Feedwater and Level Control System

The first term of Eq. (9) represents the simple proportional increase of the level due to water filling, and the second term describes the shrink effect that changes with the power. Other transfer functions are determined in a similar manner. Using these open loop transfer functions, the steam generator system can be represented by the block diagram shown in Fig. 4.

In Fig. 4, $H_i(s, p)$, $i = 1, 2, 3, 4$, are the open loop transfer functions between the level and each input vector element of $N_i(s)=[\Delta W_F(s), \Delta W_S(s), \Delta T_P(s), \Delta T_F(s)]$, respectively. $V_i\ (s, P)$ $i = 1, 2, 3, 4$, are open loop transfer functions between the steam generator power and the input vector. The feedwater station is represented by 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 steam generator thermal power, P.
2) The system is comprised of an open loop for power and a closed loop for level.
3) In regards to the power loop train, all of the input vector elements act as system inputs, and for the level train, $H_i(s, p)$, $i = 2, 3, 4$, act on the system as disturbances.
4) The system is a MIMO; one of the system outputs is tracked, the other is regulated.

3.2 Application of MPC to the Steam Generator Feedwater and Level Control System

In order to apply the MPC method to the steam generator feedwater and level control, the overall system structure is rearranged, as shown in Figs. 5(a) and (b). This configuration is consistent with the MPC structure of Fig. 2.

Two controllers were designed. The first was the MPC feedwater controller (Fig. 5(a)) and the second was the MPC level controller (Fig. 5(b)).

Feedwater Controller

Since the feedwater control system is a servo system in which the feedwater flow rate follows the steam flow rate, at least one integrator is necessary. The valve station is assumed to be a first order lagger whose time constant is 1 sec. The rationales for this assumption are explained in [2] and [3].

The MPC structure of the feedwater station is described in Fig. 5(a). The MPC controller design is an optimization problem described by the following:

$$\begin{aligned}
&\textit{Determine}\ \Delta u(k|k),\ \Delta u(k+1|k),\ \cdots, \Delta u(k+m-1|k) \qquad (10)\\
&\textit{To minimize the cost of}\ \sum_{i=0}^{p-1}\left[\sum_{j=1}^{n_y}\left|w_{i+1,j}\left(y_j(k+i+1|k)-r_j(k+i+1)\right)\right|^2\right]\\
&+\sum_{i=0}^{p-1}\left[\sum_{j=1}^{n_u}\left|w_{i,j}\left(\Delta u_j(k+i|k)\right)\right|^2+\sum_{j=1}^{n_u}\left|w_{i,j}\left(u_j(k+i|k)-u_{j,target}(k+i)\right)\right|^2\right]
\end{aligned}$$

,where p and m are the prediction and control horizons, respectively.

With the horizons of p=10, m=2, and the sampling period of T_s=0.1sec, the optimization problem described by Eq. (10) is solved. With regard to the weights of [W_y, W_u, $W_{\Delta u}$], three cases of [10, 3, 20](Case A), [10, 1, 20] (Case B) and [10, 5, 20](Case C) are considered after many simulations. It needs to be noted that the relative values of the weights are meaningful. Since the rapid movement of the feedwater valve is not preferable, $W_{\Delta u}$ is given as two times larger than W_y. The effect of W_u is then investigated by changing its value.

Given the constraints of $|u|\leq 1, |\Delta u|\leq 3$ the system responses are presented in Fig. 6. These constraints are imposed considering the mechanical characteristics of

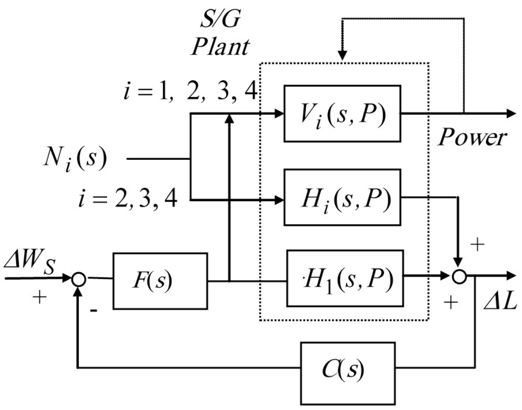
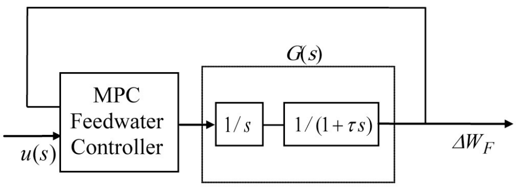
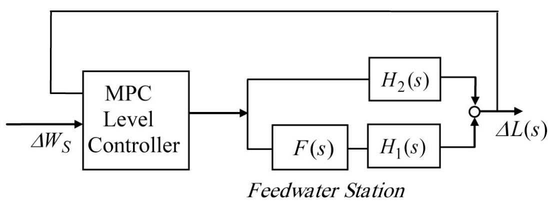


Fig. 4. Block Diagram of Steam Generator System

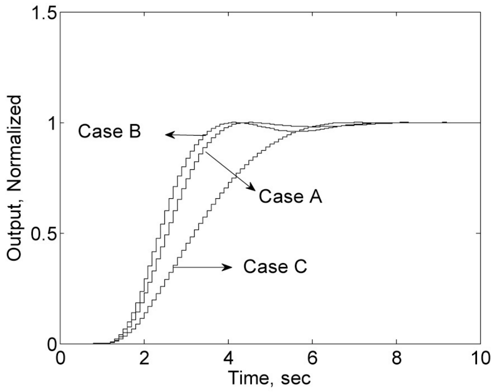


(a) Feedwater Station

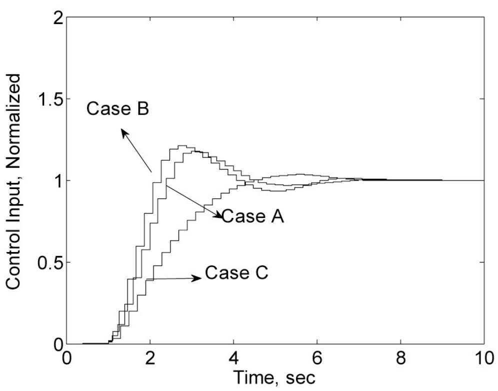


(b) Overall System

Fig. 5. System Configuration (a) Feedwater Station (b) Overall System



(a) Output



(b) Control Effort

Fig. 6. System Responses of Feedwater Station (a) Output (b) Control Effort

the feedwater station. Among these cases, the weight combination of Case C gives a good result. Although the system speed is rather slow, the control effort is small.

The MPC controller is a MISO (Multi Inputs, Single Output) system, as shown in Fig. 5(a). It receives two inputs and yields one output, and can be expressed by the transfer functions of:

$$H_{MPC}(z)=\frac{\begin{pmatrix}-0.021z^3+0.0188z^2\\ 0.2506z^3-0.4519z^2+0.2108z\end{pmatrix}}{z^3-2.614z^2+2.287z-0.6689},\ T_s=0.1sec \quad (11)$$

Level Controller

As described in Fig. 4, the four variables [$\Delta W_F(s)$, $\Delta W_S(s)$, $\Delta T_P(s)$, $\Delta T_F(s)$] act on the steam generator plant and $H_i(s)$ is the transfer function between each variable and level. Then, the relationship between the level and these variables in the steam generator is:

$$\Delta L(s)=\Delta W_S(s)\cdot F(s)\cdot H_1(s)+\Delta W_S(s)\cdot H_2(s)+O(s),$$
$$O(s)=\Delta T_P(s)\cdot H_3(s)+\Delta T_{FW}(s)\cdot H_4(s) \quad (12)$$

In Eq. (12), $F(s)$ represents the feedwater station of Fig. 5 (a), and is determined by:

$$F(s)=\frac{0.2506s^3+3.225s^2+5.072s+2.807}{s^5+5.021s^4+10.48s^3+12.87s^2+8.898s+2.807} \quad (13)$$

The effects of the primary coolant temperature and feedwater temperature on the level are very small and can be neglected. Therefore, the open loop transfer function becomes:

$$G(s)=\frac{\Delta L(s)}{\Delta W_S(s)}=F(s)\cdot H_1(s)+H_2(s) \quad (14)$$

In reality, $H_i(s)$ depends on the power, and becomes less stable as the power level becomes lower. Therefore, for a conservative approach, the power is assumed to be 5%. With $H_1(s)$ and $H_2(s)$ determined at this power, and with $F(s)$, the open loop transfer function of Eq. (14) becomes:

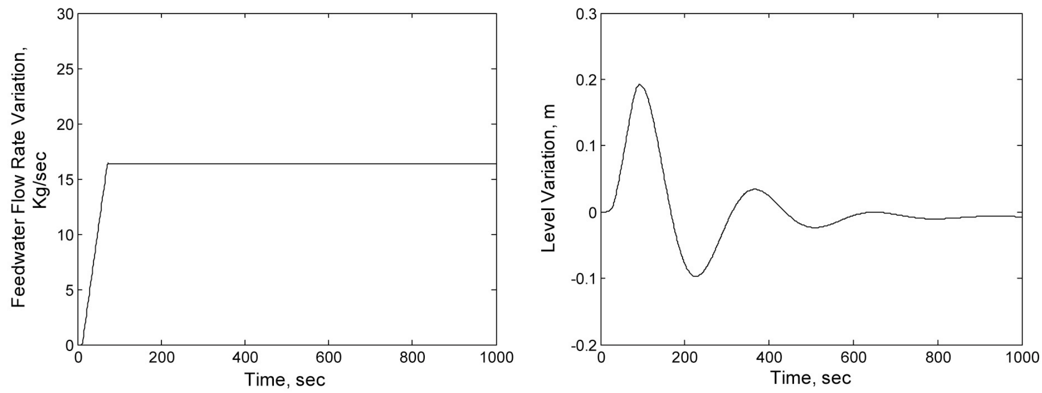
$$G(s)=\frac{0.00092s^9+0.00461s^9+\cdots+\varepsilon_1 s^2+\varepsilon_2 s+\varepsilon_3}{s^{10}+5.083s^{10}+\cdots+\varepsilon_4 s^2} \quad (15)$$
$$=\frac{0.00092s^6+0.00461s^5+\cdots+0.0088s^2+0.00295s}{s^7+5.083s^{10}+\cdots+0.1581s+0.00344}$$

The calculation procedure for determining the MPC level controller is the same as that for the feedwater controller. Numerous sets of weights are tried; with the weights [W_y, W_u, $W_{\Delta u}$] =[10 1 16], the MPC controller is determined to be:

$$C(z)=\frac{\begin{pmatrix}-0.0103z^9+0.0424z^8..+0.0116z^2\\ 0.0365z^9-0.1738z^8..+0.0143z^2+0.0018z\end{pmatrix}}{z^9-5.728z^8+14.47z^7\cdots+0.4259z-0.049},\ T_s=0.1sec \quad (16)$$

Figure 7 shows the level variation when the power is increased linearly from 5% to 10% over 60 seconds. For this, the steam flow rate is increased linearly by 0.28Kg/sec, and after 60 seconds, is held constant. The feedwater rate follows the steam flow rate almost exactly. Although the level increases rather rapidly during the initial period, due to the low power level, the peak value of the level is still much smaller than the permitted set point value, and it settles down at about 400 seconds into the transient.

The system responses shown in Fig. 7 are obtained using the fixed transfer functions, $H_1(s)$ and $H_2(s)$, that were determined at the initial steady state power of 5%. But in reality, the transfer functions change continuously with the power change during the transient. To reflect this, the transfer functions are determined at every sampling time with the power calculated at that time. This procedure, which is explained in Fig. 8, is named dynamic calculation.



(a) Feedwater Flow Rate Variation (b) Level Variation

Fig. 7. System Responses (a) Feedwater Flow Rate Variation (b) Level Variation

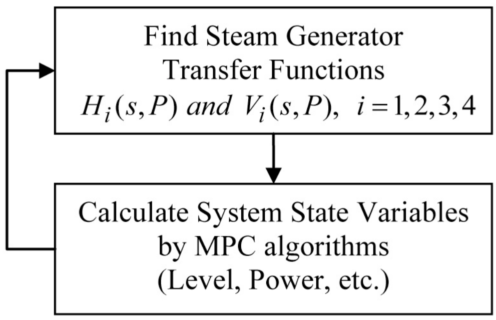
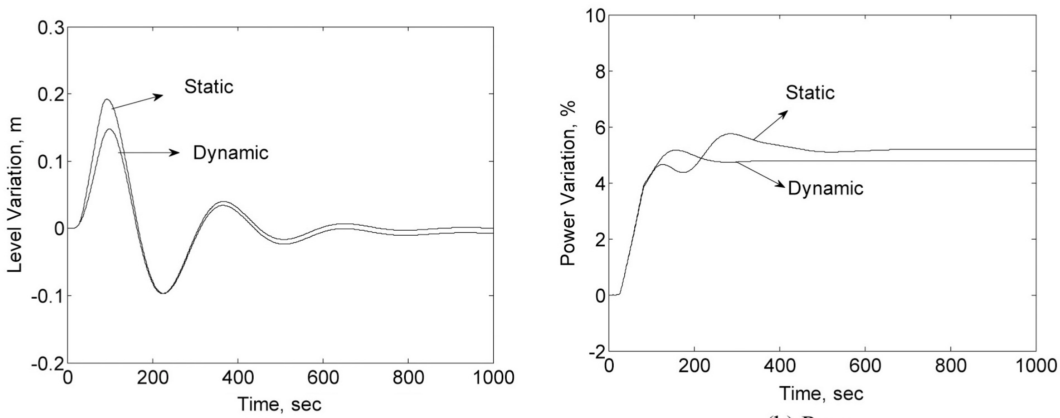


Fig. 8. Dynamic Calculation of State Variables of Steam Generator



(a) Level (b) Power

Fig. 9. Comparison between Static Calculation and Dynamic Calculation (a) Level (b) Power

Figure 9 shows the comparison of the system responses in regards to the static and dynamic calculations. The dynamic calculation gives better results. The peak value of the level obtained by the dynamic calculation is much less than that found by the static calculation. In addition, there is no steady state error in the dynamic calculation. For the dynamic calculation case, the thermal power of the steam generator follows the command signal in a satisfactory manner. These improvements arise from the fact that the system becomes more stable as the power increases.

4. SUMMARY

A nuclear steam generator presents difficulties in regards to level control, particularly at low power. It shows a non-minimum phase, in terms of control, at low power. In addition, the steam generator model has a great deal of intrinsic uncertainty because of its thermal hydraulic mechanisms. Many controllers have been developed using various algorithms in order to cope with uncertainties, but they tend to overly stress the stability, and therefore, their performance is not very satisfactory. In this study, the model predictive control (MPC) method is applied to the design of a steam generator level control system. The basic concept is similar to the action of a human operator in that the MPC anticipates the future responses of the system. However, the MPC uses a process model to compute the output predictions, and so the model must be exact.

The MPC design has two parts. The first one is the MPC controller design for the feedwater station. Then in the second phase, the feedwater station is augmented to the steam generator, and the MPC level controller is determined. The design of the MPC controller is a kind of optimization problem, and it depends on the constitution of the cost function. Simulations have been run in order to verify the performance of the designed controllers. Two cases of static and dynamic calculations were considered. The static calculation used the fixed transfer functions that are determined with the initial power level. On the other hand, in the dynamic calculation, the transfer functions were redefined at every sampling instant. The results show that the performance of the MPC controllers was satisfactory. The system employing the MPC controllers followed the command signal at a good speed, and the output responses were moderate without salient peaks and sustaining oscillations.

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