보일러-터빈 시스템을 위한 이동구간예측제어기 설계

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Design of Receding Horizon Control for Boiler-Turbine Systems

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Abstract - In this paper, we suggest a design scheme of receding horizon predictive control(RHPC) for boiler-turbine systems whose dynamics are given in nonlinear equations. RHPC is designed for linear state space models which are obtained at a nominal operating point of the boiler-turbine system. In this consideration, the boiler is operated in a sliding pressure mode, in which the refenence value of drum pressure is changing according to the electrical power generation. The reference values of the system outputs are prefiltered before they are fed to the RHPC in order to compensate the linearization errors. Simulation results show that the proposed controller provides acceptable performances in both of the cases of 'steep and small changes' and 'slow and large changes' of power demand and yields the effect of modest coordination of connventional PID schemes such as boiler-following and turbine-following control.

1. 서 론

The effective control of the boiler-turbine system is essential for energy saving and the stability of a power plant. The boiler-turbine unit is a complex interactive system and variations in one of the controlled parameters will be accompinied or followed by directly associated disturbances in others.

When the boiler-turbine system is controlled using conventional PID, there are two basic control techniques. One is boiler-following control and the other is turbine-following control[4]. In the boiler-following control, the demand signal of electrical power is applied to the governor valve(turbine throttle valve) and it responds immediately to the demand signal by manipulating the steam flow rate. Manipulating the steam flow rate causes alteration in the steam pressure ,and in turn, it is corrected by the boiler's steam pressure controller.
The advantage of boiler-following control is its rapid response to small scale changes of power demand signal. The main drawback of boiler-following control is that the performance may deteriorates when the steam generations, which depends on boiler dynamics and is slow compared to turbine dynamics, can not follow the change of electrical demand signal.

In the turbine-following control, the power demand signal is applied to the firing rate input and the governor valve is used to maintain the steam pressure of boiler at a desired value. The turbine-following control can not meet a rapid change of the power demand signal. This arrangement, however, will maintain generations at the desired value in the long term. Thus, in order to obtain optimum performance from a boiler-turbine unit as a whole using, it is necessary to couple together the control of both the boiler-following and the turbine-following.

It is expected that a multivariable controller such as LQG/LTR or receding horizon predictive control(RHPC)[1] provides a systematic basis for designing control system for the boiler-turbine unit and yields a modest coordination of boiler-following and turbine-following control. Furthermore, in many cases future trajectory of desired electrical power is available and the RHPC can take advantage of the predicted trajectory information to obtain the required power with minimum disturbances. Design of boiler-turbine control systems using LQG/LTR method is described in [2]. And application of GPC to a boiler-turbine unit is considered in [3]. In these studies, however, the tracking performance for various types of demand signals is not considered and they did not considered the case in which the demand signal of drum-pressure is varying according to the demand signal of electrical power.

In this paper, we propose a design of RHPC for a boiler-turbine system. The design objective is to obtain a good tracking performances for both cases of 'steep and small changes' and 'slow and large changes' of demand signals of electrical power through the whole operating range. We assume that the boiler-turbine system is operated in the sliding pressure mode in which the reference signal of drum pressure is scheduled so that the drum pressure is kept in a value just enough to maintain the current values of electrical output. By using this sliding mode control, we can increase the efficiency of the system[4]. We use a prefilter to the reference signal of drum pressure in order to prevent drum pressure being forced to change faster than its time constant. A nonlinear boiler-turbine model which are obtained by Bell and Åstrom[5] is considered in the design of RHPC.

In Section 2, the boiler-turbine model and its control objectives are discussed. We describe the design of RHPC for the boiler-turbine system. in section 3, where the problems of how to determine the sampling time, prefilter and reference values of drum pressure are dicussed.. In Section 4, we obtained simulation results of the suggested RHPC and compared them with those of conventional PID for various types of demand signals.

2. 보일러-터빈 모델

We use the nonlinear model for 160MW boiler-turbine system which is obtained by Bell and Åstrom[5] and its validity is well

내용 \ equilibrium point	point 1	point 2	point 3
$x_1(\,kg/cm^2)$	100	140	160
x_2(MW)	40	100	160
$x_3(\,kg/cm^3)$	87.79	164.67	239.2204
u_1	0.233	0.492	0.7314
u_2	0.527	0.747	0.9456
u_3	0.276	0.627	0.9647

Table 1. Equilibrium Points

estabilished. The nonlinear model is given as follows.

$$\dot{x}_1 = -0.0018u_2x_1^{9/8}+0.9u_1-0.15u_3$$
$$\dot{x}_2 = (0.073u_2-0.016)x_1^{9/8}-0.1x_2$$
$$\dot{x}_3 = (141u_3-(1.1u_2-0.19)x_1)/85 \tag{1}$$
$$y_1 = x_1,\quad y_2=x2$$
$$y_3 = \frac{0.05}{(0.13073x_2+100a_{cs}+q_{e/9}-67.975)}$$

where

$$a_{cs} = \frac{(1-0.001538x_3)(0.8x_1-25.6)}{x_3(1.0394-0.0012304x_1)}$$
$$q_e = (0.854u_2-0.147)x_1 +45.59u_1-2.514u_3-2.096$$

and the state variables x_1, x_2, and x_3 represent steam pressure(kg/cm^2), electrical power(MW), and density(kg/cm^3) of the fluid in the drum, respectively. The control input u_1 is the position of the fuel valve, u_2 is the position of the governer valve which controls the steam flow from boiler to turbine, and u_3 is the position of valve which controls the feedwater flow. The control inputs are normalized and have some constraints as follows:

$$0<u_1\le 1,\quad |\dot{u}_1|\le 0.007/\text{sec}$$
$$0\le u_2\le 1,\quad -2/\text{sec}\le \dot{u}_2\le 0.02/\text{sec} \tag{2}$$
$$0\le u_3\le 1,\quad |\dot{u}_2|\le 0.05/\text{sec}$$

The output y_3 represents drum level(m), a_{cs} the steam quality, q_e the evaporation rate.

We assume that the boiler-turbine system is operated via feedback control in the range of 40MW to 160MW electrical power generation, where 40MW is the 25% of the maximum power generation. The drum pressure should be maintained at a level which is enough to maintain the desired electrical power generation. If the boiler-turbine should be operated with a fixed demand value of drum pressure, the fixed demand value should be large enough to maintain the maximum electrical power generation and this fact decreases the efficiency of the operation. In this paper, we will consider the case in which the demand value of drum pressure varies according to the change of electrical load, and it is referred to as 'sliding-pressure' or 'variable-pressure control'. This sliding-pressure control results in more efficient operation at lower load and has several additional benefits compared to 'fixed-pressure' control[4]. Steep variation in drum pressure, however, should be avoided to prevent the fatigue of the boiler. Thus, we will employ a prefilter to the reference signals of drum pressure. In order to obtain proper reference values of drum pressure according to the electrical power, we search for several equilibrium points which is defined as follows.

Definition : When we represent the nonlinear system (1) as $\dot{x}=f(x,u)$ and $y=g(x,u)$, where $x=[x_1\ x_2\ x_3]'$, $u=[u_1\ u_2\ u_3]'$, and $y=[y_1\ y_2\ y_3]'$, 'equilibrium points with output y' are pairs of $(x_e(y)\ \ u_e(y))$ satisfying:

$$\begin{aligned} 0 &= f(x_e, u_e) \\ y &= g(x_e, u_e), \end{aligned} \tag{3}$$

and the input saturation condition (2)).

From the relation (1), we can find unique $(x_e(y)\ \ u_e(y))$ for any given y. Considering the input saturation and operating range of the boiler-turbine system, we selected three equilibrium points. Two of them are the boundary points and the other is the center point of the operating range as Table 1. The reference values of drum pressure is scheduled according to these three equilibrium points, which will be explained later.

We will obtain a nominal plant model by linearizing the boiler-turbin plant at the center point of operating range among the above three equilibrium points. And the linearized model can be written as:

$$\begin{aligned} \dot{x}_\delta(t) &= A(y^0)x_\delta(t) + B(y^0)u_\delta(t) \\ y_\delta(t) &= C(y^0)x_\delta(t) + D(y^0)u_\delta(t) \end{aligned} \tag{4}$$

where y^0 is an equilibrium point and

$$A(y^0) = \frac{\partial f}{\partial x}(x^0, u^0), \quad C(y^0) = \frac{\partial g}{\partial x}(x^0, u^0)$$
$$B(y^0) = \frac{\partial f}{\partial u}(x^0, u^0), \quad D(y^0) = \frac{\partial g}{\partial u}(x^0, u^0)$$

and

$$\begin{aligned} x_\delta(t) &= x(t) - x^0 \\ u_\delta(t) &= u(t) - u^0. \\ y_\delta(t) &= y(t) - y^0. \end{aligned} \tag{5}$$

We must take note of the fact that at these operating points the matrix D of the system (4) is not zero. This is different from the standard case of RHPC.

3. 이동구간예측제어기 설계

Considering the responses of the drum pressure and electrical power from the step change of governer valve, we selected sampling time as 4sec. A discrete-time state space model with sampling time 4sec is obtained from the system (4) as follows[6]:

$$\begin{aligned} x_\delta(k+1) &= \phi(y^0)x_\delta(k) + \theta(y^0)u_\delta(k) \\ y_\delta(k) &= C(y^0)x_\delta(k) + D(y^0)u_\delta(k) \end{aligned} \tag{6}$$

where $\Phi = e^A$ and $\theta = \int_k^{k+1} e^{A(k+1-\mathrm{tau})} Bd\tau$. We augment the discrete-time system (6) by adding integerator as the diagram:

Then the augmented linearized discre-time system is obtained as follows:

$$\begin{aligned} x_a(k+1) &= \phi_a x_a(k) + \theta_a \Delta u_\delta(k) \\ y_\delta(k) &= C_a x_a(k) \end{aligned} \tag{7}$$

where

$$\phi_a = \begin{bmatrix} \phi & \theta \\ 0 & I_{3\times3} \end{bmatrix} \quad \theta_a = \begin{bmatrix} 0 \\ I_{3\times3} \end{bmatrix} \quad C_a = [C \quad D].$$

We must take note of the fact that in the augmented system the output is not directly affected by the input i.e. D matrix is concealed in C_a. Thus, the design procedure of RHPC for the system (7) resembles that of [1]. If the future demand signals of steam pressure (y_{1r}), electrical power y_{2r} and drum level y_{3r} are known, then the incremental demand signals for the linearized system (7) are given as $y_{\delta r} = y_r - y^0$, where $y_r = [y_{1r}\ y_{2r}\ y_{3r}]'$. When the future demand signals $y_{\delta r}(k+j)$, $j = 0, \cdots, N+N_F$ are known, we search future control inputs which minimize the following performance index for the system (7);

$$J = \sum_{j=1}^{N} |y_{\delta r}(k+j) - \hat{y}_\delta(k+j|k)|_Q + |\Delta u_\delta(k+j-1)| + \sum_{j=N+1}^{N_F} |y_{\delta r}(k+j) - \hat{y}_\delta(k+j|k)|_{Q_F}, \tag{8}$$

where $|x|_Q$ is $\frac{1}{2}x^TQx$ and $\hat{y}_\delta(k+j|k)$, $j = 1, 2, \cdots, N+N_F$ is a prediction of future output values based on output data upto k. How to determine $\hat{y}_\delta(k+j|k)$ may be considered as a design factor. In this paper, $\hat{y}_\delta(k+j|k)$ is obtained using a state estimation $\hat{x}_a(t)$ as:

$$\hat{y}(k+i) = C_a\phi_a^i \hat{x}_a(k) \quad i = 1, 2, \cdots + \sum_{j=1}^{i} C_a\phi_a^{i-j}\theta_a \Delta u_\delta(k+j), \tag{9}$$

and receding horizon dual filter(RHDF) is used to make $\hat{x}_a(k)$. RHDF is structually dual to RHC[1], and its gain is obtained as follows:

$$\begin{aligned} \hat{x}_a(k|k-1) &= \phi_a \hat{x}_a(k-1) + \theta_a \Delta u_\delta(k-1) \\ \hat{x}_a(k) &= \hat{x}_a(k|k-1) + K[y_\delta(k) - C_a \hat{x}_a(k|k-1)], \end{aligned} \tag{10}$$

where K is obtained from the following RDE:

$$\begin{aligned} K &= P(H)C_{a'}[C_aP(H)C_{a'} + \xi]^{-1} \\ P(i+1) &= \phi_a P(i)\phi_{a'} + \phi_a P(i) C_{a'}(C_aP(i)C_{a'} + \xi)^{-1}C_aP(i)\phi_{a'} \end{aligned} \tag{11}$$

with $P(0) = \xi_F$. The filtering horizon(H), measurement error(ξ) and initial state error covariance(ξ_F) are design factors. Using (9), the cost function (8) can be rewritten as follows:

$$J = |Y_{\delta r}(k) - V\hat{x}_a(k) - WU(k)|_{\overline{Q}} + |U(k)|_\lambda + |Y_{\delta rF}(k) - V_F\hat{x}_p(k) - W_FU(k)|_{\overline{Q_F}}$$

where

$$W \equiv \begin{bmatrix} C_a\theta_a & 0 & 0 & \cdots & 0 & 0 \\ C_a\phi_a\theta_a & C_a\theta_a & 0 & \cdots & 0 & 0 \\ \cdot & \cdot & \ddots & & \vdots & \vdots \\ \cdot & \cdot & & \ddots & 0 & 0 \\ C_a\phi_a^{N-1}\theta_a & C_a\phi_a^{N-2}\theta_a & \cdot & \cdots & C_a\theta_a & 0 \end{bmatrix}$$

$$W_F \equiv \begin{bmatrix} C_a\phi_a^N\theta_a & \cdot & \cdot & C_a\theta_a \\ C_a\phi_a^{N+1}\theta_a & \cdot & \cdot & C_a\phi_a\theta_a \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ C_a\phi_a^{N+N_F-1}\theta_a & \cdot & \cdot & C_a\phi_a^{N_F-1}\theta_a \end{bmatrix}$$

$$U(k) \equiv [\Delta u_\delta(k)\ \ \Delta u_\delta(k+1)\ \cdots\ \Delta u_\delta(k+N)]'$$

$$V \equiv [C_a\phi_a\ \ C_a\phi_a^2\ \cdots\ C_a\phi_a^N]'$$

$$Y_{\delta r}(k) \equiv \begin{bmatrix} y_{\delta r}(k+1) \\ y_{\delta r}(k+2) \\ \vdots \\ y_{\delta r}(k+N) \end{bmatrix} \quad V_F \equiv \begin{bmatrix} C_a\phi_a^{N+1} \\ C_a\phi_a^{N+2} \\ \vdots \\ C_a\phi_a^{N+N_F} \end{bmatrix}$$

$$Y_{\delta rF}(k) \equiv \begin{bmatrix} y_{\delta r}(k+N+1) \\ y_{\delta r}(k+N+2) \\ \vdots \\ y_{\delta r}(k+N+N_F) \end{bmatrix} \quad \begin{aligned} \overline{Q} &\equiv diag(Q)_N \\ \overline{Q_F} &\equiv diag(Q_F)_{N_F} \end{aligned}$$

Differentiating the cost functional J with the vector U, we get the control increment vector U(k) which minimizes J as:

$$\begin{aligned} U(k) &= (W^T\overline{Q}W + W_F^T\overline{Q}_FW_F + I)^{-1} \\ &\cdot \{W^T\overline{Q}(Y_{\delta r}(k) - V\widehat{x_{a(k)}}) \\ &+ W_F^T\overline{Q}_F(Y_{\delta rF}(k) - V_F\hat{x}_a(k))\}. \end{aligned}$$

The first 3 element of U(k) constitute the increments of the current control input vector as follows:

$$\Delta u(k) = Z\{W^T\overline{Q}(Y_{\delta r}(k) - V\hat{x}_a(k)) + W_F^T\overline{Q}_F(Y_{\delta rF}(k) - V_F\hat{x}_a(k))\}, \tag{12}$$

where

$$Z \equiv [I_{3\times3}\ 0\cdots0](W^T\overline{Q}W + W_F^T\overline{Q}_FW_F + \lambda I)^{-1}.$$

A recursive solution equivalent to (12) is also available as in [1].

Assume that the reference signals $Y_{\delta r}$ and $Y_{\delta rF}$ are remain constant and the closed loop system with the control (12) reached at an equilibrium points of the system (1), then $\Delta u(k)$ in Equation (12) is zero and elements of $V\hat{x}_a(k)$

$= Y_{\delta r}$ and $V_F\widehat{x_a}(k) = Y_{\delta rF}$ becomes the estimated future outputs of system (6), which are also constant. We must take note of the fact that $V\widehat{x_a}(k) = Y_{\delta r}$ and $V_F\widehat{x_a}(k) = Y_{\delta rF}$ do not guarantee that outputs of system (1) are equal to the constants reference values since Equation (12) is the linear approximation of the nonlinear system (1). Thus, prefilters which modifies the reference values so that $V\widehat{x_a}(k) = Y_{\delta r}$ and $V_F\widehat{x_a}(k) = Y_{\delta rF}$ implies zero or negligible are required.

4. 모의실험 결과

We simulated the cases of 'steep and small changes' and 'slow and large changes' of power demand. Linear model (6) is obtained at the point 2 of Table 1. The reference value of steam pressure(x_1) is determined via linear interpolation between the equilibrium points1,2,3 of the table 1 for a given reference values of x_2.

Fig.1 to Fig.2 shows that offset errors are not negligable for large deviation of the plants values from those of equilibrium point 2. Fig.3 to Fig.4 shows that the proposed control obtains satisfactory performance with adequate prefilter.

In these cases, $N=15$, $N_F=2$, $Q=diag(10,50,60)$, $R=diag(10,100,5)$, $Q_F=diag(200,100,1200)$ are used.

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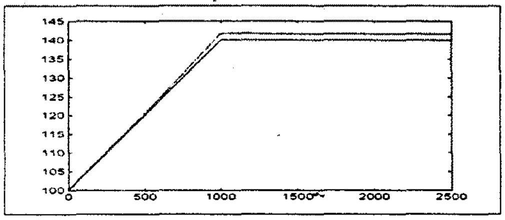

Fig. 1 Electrical Power(MW, without prefilter)

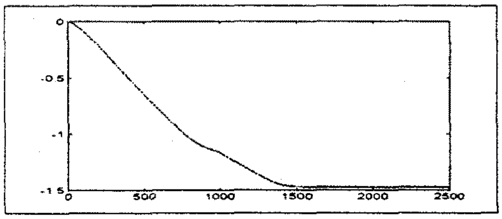

Fig. 2 Drum Level(without prefilter)

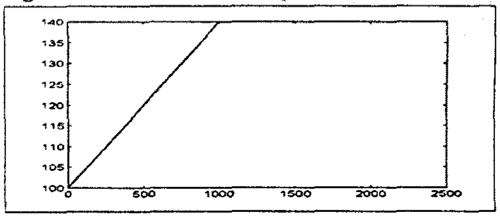

Fig. 3 Electrical Power(with prefilter)

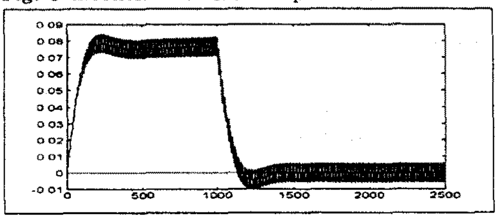

Fig. 4 Drum Level(with prefilter)

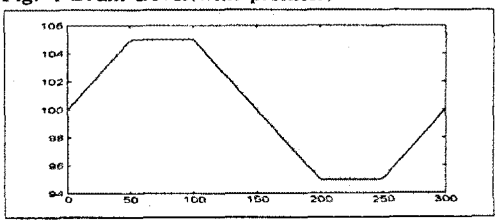

Fig. 4 Electrical Power(short-term change)

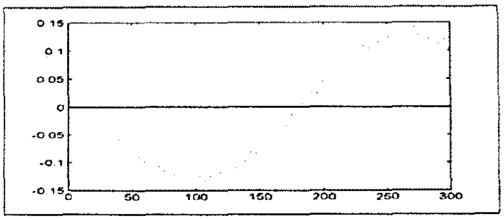

Fig. 6 Drum Level(short-term change)