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Fault Tolerant Control for Kori Unit 1 Steam Generator

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1. Introduction

In order to implement more reliable control systems, failures of a controller, a sensor and an actuator should be taken into consideration in the process of control system design. Traditionally there have been two approaches for dealing with fault-tolerant control problem: active redundancy and passive redundancy. Active redundancy has no reconfiguration part to take an action such as diagnosing and selecting intact controller when a controller failure occurs, that is, one controller guarantees the system stability and performance under failure of the other controller. Meanwhile, passive redundancy has reconfiguration parts which supervise the system, reject the faulty controller, and select the sound controller which performs the mission.

Active redundancy structure for fault-tolerant control is focused in the paper and design methods of fault-tolerant state feedback control and fault-tolerant output feedback control are proposed, which makes control a system reliable while guaranteeing stability and performance in the sense of H_∞ norm, in the face of controller failures in the dual-controller configuration. The proposed method is applied to Kori Unit 1 steam generator level control system. The results show that the steam generator water level is well controlled in the situation of one controller failure

2. Fault-Tolerant Control

Consider the fault-tolerant control system shown in Figure 1 and plant is a linear time-invariant systems described by state-space equations

$$\dot{x} = Ax + B_1\omega + B_2u,\ z = C_1x,\ y = C_2x\ . \qquad (1)$$

The controlled system depicted in Figure 1 is said to be fault-tolerant if the following conditions are satisfied 1) when both controllers operate simultaneously, the controlled system is stable 2) when only one of controllers is in operation, the controlled system is stable. The controlled system is fault-tolerant and has H_∞ norm from the disturbance to the regulated output less than the positive, γ, then the controlled system is said to be fault-tolerant with γ disturbance attenuation. That is, in the normal mode, both identical controllers C_1 and C_2 are operational and the system is stable. If either controller is fail, the system is still stable, even the performance of the closed-loop system might be degraded adversely.

2.1 Fault-tolerant state-feedback control

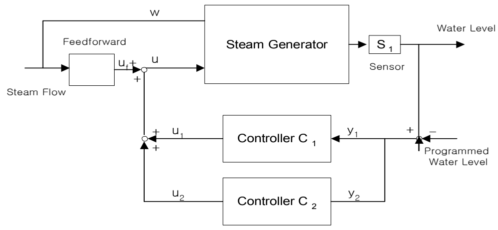

Figure 1: Structure of fault-tolerant control of steam generator of Kori Unit 1.

Consider where both equivalent C_1 and C_2 are in operation and each is state feedback controller, K. Then, the total control input, u, is

$$u = u_1 + u_2 = 2Kx\ .$$

The closed loop system can be written as

$$\dot{x} = (A + 2BK)x + \begin{bmatrix} B_1 & 0 \end{bmatrix}\begin{bmatrix} \omega \\ u \end{bmatrix},\ z = C_1x,\ y = C_2x\ . \qquad (2)$$

Next consider that one controller is in operation and the other is in fault. It is assumed that faulty controller gives the output u_0 irrespective of controller input and it belongs to $L_2[0, \infty)$. Here we assume that the intact controller is C_1 and the faulty C_2. That is, the total control input, u, is

$$u = u_1 + u_2 = u_1 + u_0\ .$$

The closed loop system can be written as

$$\dot{x} = Ax + \begin{bmatrix} B_1 & B_2 \end{bmatrix}\begin{bmatrix} \omega \\ u_0 \end{bmatrix} + B_2u_1,\ z = C_1x,\ y = C_2x\ . \qquad (3)$$

The fault-tolerant control in the sense of H_∞-norm is converted into H_∞ output-feedback control that simultaneously stabilizes two systems, (2), (3) and satisfies the H_∞ norm from the system disturbance to the controlled output signal. This is equivalent to H_∞ output-feedback control for uncertain linear time invariant systems time invariant system with state-space matrices varying in a polytope:

$$\dot{x} = Ax + \widetilde{B}_1\omega + \widetilde{B}_2u,\ z = C_1x,\ y = C_2x$$
$$(\widetilde{B}_1\ \widetilde{B}_2) \in Co\{(B_{1k}\ B_{2k}) : k = 1,2\}, \qquad (4)$$
$$B_{11} = \begin{bmatrix} B_1 & B_2 \end{bmatrix}, B_{12} = \begin{bmatrix} B_1 & 0 \end{bmatrix}, B_{21} = B_2,\ B_{22} = 2B_2$$

The problem of finding state feedback controller, K, can be converted into seeking a single quadratic Lyapunov function that enforces the design specifications for all systems in the polytope. It leads to the following LMIs:

Theorem 1 The closed-loop system (1) under state-feedback control u_1=Kx, u_2=Kx, is fault-tolerant with γ disturbance attenuation if there exists a solution of

LMIs (5) with a common Lyapunov function, X > 0. The corresponding state-feedback gain is give by K = LX.

$$\begin{bmatrix} AX_2 + B_{22}L + X_2A^T + L^TB_{22}^T & B_{11} & X_2C_1^T \\ B_{11}^T & -I & 0 \\ C_1X_2 & 0 & -\gamma^2 I \end{bmatrix} < 0$$
$$\begin{bmatrix} AX_3 + B_{21}L + X_3A^T + L^TB_{21}^T & B_{12} & X_3C_1^T \\ B_{12}^T & -I & 0 \\ C_1X_3 & 0 & -\gamma^2 I \end{bmatrix} < 0$$
$$\begin{bmatrix} AX_1 + B_{21}L + X_1A^T + L^TB_{21}^T & B_{11} & X_1C_1^T \\ B_{11}^T & -I & 0 \\ C_1X_1 & 0 & -\gamma^2 I \end{bmatrix} < 0 \qquad (5)$$
$$\begin{bmatrix} AX_4 + B_{22}L + X_4A^T + L^TB_{22}^T & B_{12} & X_4C_1^T \\ B_{12}^T & -I & 0 \\ C_1X_4 & 0 & -\gamma^2 I \end{bmatrix} < 0$$

Proof: Let single Lyapunov function $X := X_1 = X_2 = X_3 = X_4 > 0$. These conditions of (5) are jointly convex in K and X, by a simple change of variable, $L = KX$, we can obtain a quadratic stabilizability with γ attenuation.

$$\begin{aligned} A_{cl1} &= A + B_{21}K,\ B_{cl1} = B_{11}, C_{cl1} = C_1, \\ A_{cl2} &= A + B_{22}K, B_{cl2} = B_{11}, C_{cl2} = C_1, \\ A_{cl3} &= A + B_{12}K, B_{c13} = B_{12}, C_{cl3} = C_1, \\ A_{cl4} &= A + B_{22}K, B_{cl4} = B_{12}, C_{cl4} = C_1 \end{aligned} \qquad (6)$$

Using the realization for the closed-loop system, we can easily obtain the following the H∞ constraints which are equivalent the existence of a solution $X > 0$ to the LMIs known as the Bounded Real Lemma

$$\begin{bmatrix} A_{cli}X + XA_{cli}^T & B_{cli} & XC_{cli}^T \\ B_{cli}^T & -I & 0 \\ C_{cli}X & 0 & -\gamma^2 I \end{bmatrix} < 0, i = 0,...4. \qquad (7)$$

2.2 Fault-tolerant output-feedback control

Design of fault-tolerant output-feedback control is similar to that of fault-tolerant state-feedback control. Using the realization for the closed-loop system, we can easily obtain the following the H∞ constraints which are equivalent the existence of a solution $X > 0$ to the LMIs known as the Bounded Real Lemma

Theorem 2 There exists fault-tolerant controller with γ disturbance attenuation for the system (1), if there exists a $\lambda > 0$ such that the systems (8) can be stabilized with its H_∞-norm less than γ by an output feedback control.

$$\dot{x} = Ax + \begin{bmatrix} \tilde{B}_1 & \gamma\lambda H \end{bmatrix} \begin{bmatrix} \omega \\ u_0 \\ \tilde{\omega} \end{bmatrix} + \tilde{B}_2 u,$$
$$\begin{bmatrix} z \\ \tilde{z} \end{bmatrix} = \begin{bmatrix} C_1 \\ 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ \frac{1}{\lambda}E_1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ u_0 \\ \tilde{\omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{\lambda}E_2 \end{bmatrix} u_1 \qquad (8)$$
$$H = B_2, E_1 = \begin{bmatrix} 0 & \frac{1}{2}I \end{bmatrix}, E_2 = \frac{1}{2}I, \tilde{B}_1 = \begin{bmatrix} B_1 & \frac{1}{2}B_2 \end{bmatrix}$$
$$\tilde{B}_2 = \frac{3}{2}B_2, \begin{bmatrix} \Delta B_1 & \Delta B_2 \end{bmatrix} = HF(t)\begin{bmatrix} E_1 & E_2 \end{bmatrix}, F(t) = I$$

Proof: In the sense of H_∞-norm the system (8) is equivalent to uncertain LTI system (1) of which uncertainties are introduced to present the condition of fault-tolerant with γ disturbance attenuation. When the output feedback controller $u = K y$ satisfies H_∞-norm performance of (8), it achieves fault-tolerant conditions for original system (1).

3. Simulation for Kori Unit 1 steam generator water level control

The proposed fault-tolerant control is applied to Kori Unit 1 steam generator water level control, which has passive redundant structure consisting of dual controllers, common sensor and feedforward compensator. As depicted in Fig. 2, the simulation shows that where power changes at 100*sec* and the controller C_2 is in fail-zero at 150*sec*, the intact controller C_1 works properly, resulting that the water level goes to stable level after 300*sec*.

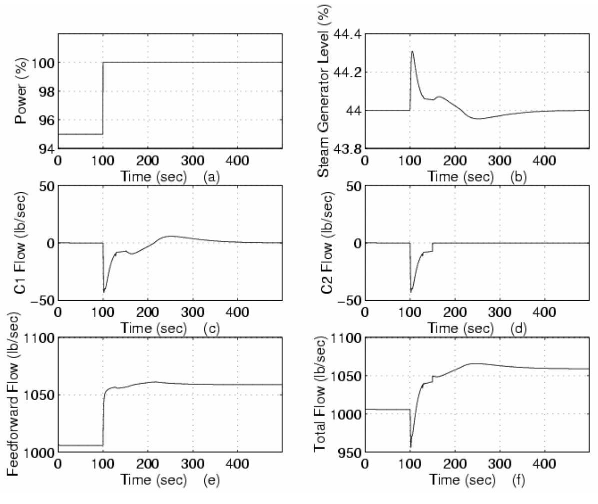

Figure 2: Simulation results of fault-tolerant control.

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