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Networked H_∞ Approach에 의한 전력계통안정화

*이상성 (ssLee6@snu.ac.kr)
*차세대지역에너지연구소 및 전력시스템연구실 (기초전력연구원), 서울대학교 130동, 신림9동, 관악구, 151-742, 서울특별시

Networked H_∞ Approach and Power System Stabilization

*Sang-Seung Lee (ssLee6@snu.ac.kr)
*RERI and PSRD (KESRI), Seoul National University 130Dong, ShinLim-9Dong, KwanAk-Gu, Seoul, 151-742, Korea

Abstract - This paper deals with power system stabilization problem using a network control system in which the control is applied through a communication channel in feedback form. Analysis and synthesis issues are investigated by modeling the packet delivery characteristics of the network as a Bernoulli random variable, which is described by a two state Markov chain. This model assumption yields an overall system which is described by a discrete-time Markov jump linear system. These employ the norm to measure the performance of the system, and they compute the norm via a necessary and sufficient matrix inequality condition.

1. Introduction

In 1989, the standard Dole, Glover, Khargoneker, and Francis (abbr. : DGKF) H_∞ controller($H_\infty C$) was presented[1]. This standard H_∞ controller has been extended to H_∞/sliding mode controller with an application to power system stabilization[2-4]. This paper is based on DGKF $H_\infty C$ and deals with the direction for power system stabilization problem using a network control system in which the control is applied through a communication channel in feedback form[5].

Analysis and synthesis issues are investigated by modeling the packet delivery characteristics of the network as a Bernoulli random variable, which is described by a two state Markov chain. This model assumption yields an overall system which is described by a discrete-time Markov jump linear system. These employ the norm to measure the performance of the system, and they compute the norm via a necessary and sufficient matrix inequality condition. Further, they derive necessary and sufficient linear matrix inequality conditions for the synthesis of the optimal controller.

In this paper, we consider analysis and synthesis problems related to NCS. We focus on closed-loop performance since this presumably yields more quantitative information than looking at closed-loop stability.

This models the packet delivery characteristics of the network as a Bernoulli (the memoryless channel) or two state Markov process. The latter is commonly used to model the fading channel. These channel models when combined with a discrete-time Markovian jump linear system(MJLS).

2. Networked Control System(NCS) based on H_∞

A networked control system (NCS) is one in which a control loop is closed via a communication channel. The use of a network will lead to intermittent losses or delays of the communicated information and may deteriorate the performance or cause instability.

This concept briefly reviews work on network modelling as well as analysis and synthesis results for NCS. For control design we would like a network model that is as simple as possible without sacrificing accuracy. Next, these models discuss analysis and synthesis results for NCS. Many results have appeared in the literature to analysis closed-loop stability in the face of network delays. These approaches can be classified as deterministic or stochastic.

i) Deterministic approaches assume the network delays time-varying but bounded and use Lyapunov theory to fine maximum delays that can be tolerated.

ii) Stochastic approaches try to prove a version of stability such as mean square stability or exponential mean square stability or exponential mean square stability.

Control synthesis results for NCSs have employed linear quadratic Gaussian(LQG) style costs, μ -synthesis, observers to compensate for delays, and results for stochastic jump systems.

Let $y_c(k)$ and $\hat{y}_c$ denote a single measurement that is sent and received respectively. If we apply these assumptions then a simple packet-loss model for the network is given by

$$\hat{y}(k)=\begin{cases} y(k), & \text{if } \theta(k)=R \\ \varnothing, & \text{if } \theta(k)=L \end{cases} \tag{1}$$

where $\varnothing$ denotes a corrupted packet of information.

This is known as erasure model for a network. $\theta(k)$ is a random process that governs the packet delivery characteristics of the network. Two state Markov process can be used to model this burst packet loss process (Fig. 1) $p_{i,j} = P_r[\theta(k+1)=j \mid \theta(k)=i]$ for $i,j \in \{L, R\}$. The bursty nature is modeled with $p_{L,L} > p_{R,L}$ and is motivated by the Gilbert-Elliott analysis of fading channels. To simplify the analysis, we assume all communicated measurements are simultaneously corrupted or received and, hence, the network can be modeled with two states

$$\hat{y}_c(k)=\begin{cases} y_c(k), & \text{if } \theta(k)=R \\ \varnothing, & \text{if } \theta(k)=L \end{cases} \tag{2}$$

where $\hat{y}_c(k)$ is the vector of communicated measurements available for feedback, $y_c(k)=[v_0\, a_0\, a_1\, a_2 a_3]^T$. The measurements available from on-board sensors are

$$y_0 = [e_0 \ldots\ldots e_4 \quad \dot{e}_0 \ldots\ldots \dot{e}_4 \quad v_1 \ldots\ldots v_4]^T \tag{3}$$

If the measurements are communicated without error $(\theta(k)=R)$, the controller can be written as $u(k)=K_1 y(k)$ where the measurement vector takes the form

$$y(k):=\begin{bmatrix} y_0(k) \\ y_c(k) \end{bmatrix}=\begin{bmatrix} C_{OL,1} \\ C_{OL,2} \end{bmatrix} x_{OL}(k)+\begin{bmatrix} D_{OL,1} \\ D_{OL,2} \end{bmatrix} r_0(k) \tag{3}$$

If the measurements are received with an error $(\theta(k)=L)$, then each controller discards the corrupted packet and implements the modified control action that uses only measurements from on-board sensors:

$$u_i(k)=k_d * \dot{e}_i(k)+k_p * e_i(k) \quad \text{for } i=0,\ldots,4 \tag{4}$$

In this case, the controller can be written as $u(k)=K_0 y(k)$ with the appropriate gain matrix K_0. To summarize, each follower uses the following switching logic:

$$\begin{aligned} u_i(k) = {} & \lambda * a_0(k)+(1-\lambda) * a_{i-1}(k) \\ & + k_0 * (v_0(k)-v_i(k)) \\ & + k_d * \dot{e}_i(k)+k_p * e_i(k), \quad \text{if } \theta(k)=R \end{aligned} \tag{5}$$

$$u_i(k)=k_d * \dot{e}_i(k)+k_p * e_i(k), \qquad \text{if } \theta(k)=L \tag{6}$$

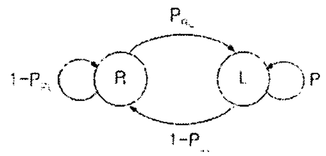

Fig. 1. Two-state Markov network model

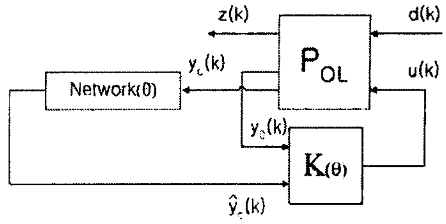

Fig. 2. Closed-loop is a jump system

3. Conclusions

In this paper, the effect of a network in the feedback loop of a control system was studied. The control performance using the H∞ gain from disturbances to errors was measured. This gain can be used to analyze the closed-loop performance of a networked control system. The computational cost of this method need further exploration since the number of Markov states number of channels. Approximation, such as lumping together the receipt/loss characteristics of several channels, may be required. These controllers also derived optimal H∞ synthesis conditions for a class of jump systems. The conditions can be applied to networked control systems with a single centralized controller. In future study, an extending recent results on distributed control to jump systems will lead to useful tools for networked systems.

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[References]

[1] J. C. Doyle, K. Glover, P. P. Khargonekar and B. A. Francis, "State-space solutions to standard H2 and H∞ control problems", *IEEE Trans. on Automatic Control*, Vol. 34, No. 8, pp. 831-847, Aug., 1989.

[2] S. S. Lee, J. K. Park and J. J. Lee, "Extending of standard H∞ controller to H∞/sliding mode controller with an application to power system stabilization", *IEE Proc. Control Theory. Appl.*, 146, (5), pp. 367-372, 1999.

[3] R. Marino and P. Tomei, *"Nonlinear control design"*, Prentice-Hall Press, 1995.

[4] Y. N. Yu, *"Electric power system dynamics"*, Academic Press, 1983.

[5] P. Seiler and R. Sengupta, "H∞ Approach to Network Control", *IEEE Trans. on Automatic Control*, Vol. 50, No. 3, pp. 356-364, March, 2005.

Appendix

A.1 Applied H∞ switching controller

$$z(t)=T(x(t)) \tag{A-1}$$

$$\dot{z}(t)=Az(t)+B_1 w_{worst}(t)+B_2 u(t) \tag{A-2}$$

$$p(t)=C_1 z(t)+D_{11} w_{worst}(t)+D_{12} u(t) \tag{A-3}$$

$$y(t)=C_2 z(t)+D_{21} w_{worst}(t)+D_{22} u(t) \tag{A-4}$$

$$\hat{z}(t) = A\hat{z}(t) + B_2 u(t) + B_1 \hat{w}_{worst}(t) + Z_\infty K_e (y(t) - \hat{y}(t)) \quad (A-5)$$

$$\hat{w}_{worst}(t) = \gamma^{-2} B_1^T X_\infty \hat{z}(t) \quad (A-6)$$

$$\hat{y}(t) = C_2\hat{z}(t) + \gamma^{-2} D_{21} B_1^T X_\infty \hat{z}(t) = [C_2 + \gamma^{-2} D_{21} B_1^T X_\infty]\hat{z}(t) \quad (A-7)$$

$$K_c = \tilde{D}_{12}(B_2^T X_\infty + D_{12}^T C_1) \quad (A-8)$$

$$\tilde{D}_{12} = (D_{12}^T D_{12})^{-1} \quad (A-9)$$

$$K_e = (Y_\infty C_2^T + B_1 D_{21}^T)\tilde{D}_{21} \quad (A-10)$$

$$\tilde{D}_{21} = (D_{21}D_{21}^T)^{-1} \quad (A-11)$$

$$Z_\infty = (I - \gamma^{-2} Y_\infty X_\infty)^{-1} \quad (A-12)$$

$$X_\infty = Ric\begin{bmatrix} A - B_2\tilde{D}_{12}D_{12}^TC_1 & \gamma^{-2}B_1B_1^T - B_2\tilde{D}_{12}B_2^T \\ -\tilde{C}_1^T\tilde{C}_1 & -(A - B_2\tilde{D}_{12}D_{12}^TC_1)^T\end{bmatrix} \quad (A-13)$$

$$\tilde{C}_1 = (I - D_{12}\tilde{D}_{12}D_{12}^T)C_1 \quad (A-14)$$

$$Y_\infty = Ric\begin{bmatrix}(A - B_1\tilde{D}_{21}D_{21}^TC_2)^T & \gamma^{-2}C_1C_1^T - C_2^T\tilde{D}_{21}C_2 \\ -\tilde{B}_1\tilde{B}_1^T & -(A - B_1\tilde{D}_{21}^T\tilde{D}_{21}C_2)\end{bmatrix} \quad (A-15)$$

$$\tilde{B}_1 = B_1(I - D_{21}^T\tilde{D}_{21}D_{21}) \quad (A-16)$$

$$u(t) = -K_c\hat{z}(t) \quad (A-17)$$

$$K(s) = \begin{bmatrix} A_1 & Z_\infty K_e \\ -K_c & 0\end{bmatrix} \quad (A-18)$$

$$A_1 := A - B_2K_c - Z_\infty K_e C_2 + \gamma^{-2}(B_1B_1^T - Z_\infty K_e D_{21} B_1^T)X_\infty \quad (A-19)$$

$$\begin{bmatrix}\dot z(t)\\ \dot{\hat z}(t)\end{bmatrix} = \begin{bmatrix} A & -B_2K_c \\ Z_\infty K_e C_2 & A_2\end{bmatrix}\begin{bmatrix} z(t)\\ \hat z(t)\end{bmatrix} + \begin{bmatrix} B_1 \\ Z_\infty K_e D_{21}\end{bmatrix} w_{worst}(t) \quad (A-20)$$

$$\begin{bmatrix} p(t)\\ y(t)\end{bmatrix} = \begin{bmatrix} C_1 & -D_{12}K_c\\ C_2 & 0\end{bmatrix}\begin{bmatrix} z(t)\\ \hat z(t)\end{bmatrix} + \begin{bmatrix}0\\ D_{21}\end{bmatrix} w_{worst}(t) \quad (A-21)$$

$$\begin{aligned} A_2 := &A - B_2K_c + \gamma^{-2}B_1B_1^TX_\infty \\ &- Z_\infty K_e(C_2 + \gamma^{-2}D_{21}B_1^TX_\infty) \end{aligned} \quad (A-22)$$

$$\begin{aligned}\dot z(t) &= Az(t) + B_1 w_{worst}(t) + B_2 u(t) \\ &= Az(t) + B_1(\gamma^{-2}B_1^TX_\infty)z(t) + B_2u(t) \\ &= (A + B_1(\gamma^{-2}B_1^TX_\infty))z(t) + B_2u(t)\end{aligned} \quad (A-23)$$

$$\sigma(z(t)) = G^Tz(t) \quad (A-24)$$

$$\dot\sigma(z(t)) = G^T\dot z(t) \quad (A-25)$$

$$V(z(t)) = \sigma^2(z(t))/2 \quad (A-26)$$

$$\dot V(z(t)) = \sigma(z(t))\dot\sigma(z(t)) \quad (A-27)$$

$$\begin{aligned} &= G^Tz(t)G^T\dot z(t) \\ &= G^Tz(t)G^T[(A + B_1(\gamma^{-2}B_1^TX_\infty)) \\ &\quad + B_2u_{NFL-W-SMC}(t)] \le 0 \end{aligned} \quad (A-28)$$

$$u^+_{NFL-W-SMC}(t) \ge -(G^TB_2)^{-1}[G^T(A + B_1(\gamma^{-2}B_1^TX_\infty))]z(t) \quad \text{for } G^Tz(t) > 0 \quad (A-29)$$

$$u^-_{NFL-W-SMC}(t) \le -(G^TB_2)^{-1}[G^T(A + B_1(\gamma^{-2}B_1^TX_\infty))]z(t) \quad \text{for } G^Tz(t) < 0 \quad (A-30)$$

$$u^{sign}_{NFL-W-SMC}(t) \ge -(G^TB_2)^{-1}[G^T(A + B_1(\gamma^{-2}B_1^TX_\infty))]z(t)\ sign(\sigma(z(t))) \quad (A-31)$$

$$u^{sign}_{NFL-W-SMC}(t) = -K_{W-SMC}z(t)\ sign(\sigma(z(t))) \quad (A-32)$$

$$K_{W-SMC} := (G^TB_2)^{-1}[G^T(A + B_1(\gamma^{-2}B_1^TX_\infty))] \quad (A-33)$$

$$u^{sign}_{NFL-H\_ISMC}(t) = -K_{W-SMC}\hat z(t)\ sign(\sigma(\hat z(t))) \quad (A-34)$$

A.2 Lie Derivatives

$$y(t) = h(x(t)) \quad (A-35)$$

$$\begin{aligned} z(t) &= T(x(t)) \\ &:= [h\ L_fh\ L_f^2h\ L_f^3h\ ....]^T \\ &= [z_1(t)\ z_2(t)\ z_3(t)\ z_4(t)\ ......]^T \end{aligned} \quad (A-36)$$

$$y(t) = Cz(t) \quad (A-37)$$

$$y(t) = L_f^0h(x(t)) \quad (A-38)$$

$$\frac{dy(t)}{dt} = L_fh(x(t)) + L_gh(x(t))u(t) \quad (A-39)$$

$$.......$$

$$\frac{d^ry(t)}{dt^r} = L_f^rh(x(t)) + L_gL_f^{r-1}h(x(t))u(t) \quad (A-40)$$

$$u(t) = g(x(t), v(t)) := -\frac{L_f^rh}{L_gL_f^{r-1}h} + \frac{1}{L_gL_f^{r-1}h}v(t) \quad (A-41)$$

where $v(t) = \frac{d^ry(t)}{dt^r}$.

$$z_1 := L_f^0 = h = \omega \quad (A-42)$$

$$z_2 := L_fh = \frac{\partial h}{\partial x}f = \frac{\partial \omega}{\partial x}f = \frac{1}{M}(T_m - T_e) \quad (A-43)$$

$$L_gh = \frac{\partial h}{\partial x}g = \frac{\partial \omega}{\partial x}g = 0 \quad (A-44)$$

$$\begin{aligned} z_3 := L_f^2h &= \frac{\partial(L_fh)}{\partial x}f = \frac{\partial}{\partial x}\Big(\frac{1}{M}(T_m - T_e)\Big) \\ &= -\frac{1}{M}(pd_9f_2 + pd_{10}f_3) \end{aligned} \quad (A-45)$$

$$L_gL_fh = \frac{\partial(L_fh)}{\partial x}g = \frac{\partial}{\partial x}\Big(\frac{1}{M}(T_m - T_e)\Big)g = 0 \quad (A-46)$$

$$\begin{aligned} z_4 := L_f^3h &= \frac{\partial}{\partial x}(L_f^2h)f = \frac{\partial}{\partial x}\Big(-\frac{1}{M}(pd_9f_2 + pd_{10}f_3)\Big)f \\ &= [pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}]f \end{aligned} \quad (A-47)$$

$$\begin{aligned} L_gL_f^2h &= \frac{\partial}{\partial x}(L_f^2h)g = \frac{\partial}{\partial x}\Big(-\frac{1}{M}(pd_9f_2pd_{10}f_3)\Big)g \\ &= [pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}]g \end{aligned} \quad (A-48)$$

where

$$pd_1 := -\frac{V_\infty}{Z_e}(R_2\cos(\delta) - X_1\sin(\delta)) \quad (A-49)$$

$$pd_2 := \frac{V_\infty}{Z_e}(X_2\cos(\delta) + R_1\sin(\delta)) \quad (A-50)$$

$$pd_3 := x_q\frac{V_\infty}{Z_e}(X_2\cos(\delta) + R_1\sin(\delta)) \quad (A-51)$$

$$pd_4 := x_d'\frac{V_\infty}{Z_e}(R_2\cos(\delta) - X_1\sin(\delta)) \quad (A-52)$$

$$pd_5 := Y_d \quad (A-53)$$

$$pd_6 := Y_q \quad (A-54)$$

$$pd_7 := x_qY_q \quad (A-55)$$

$$pd_8 := 1 - x_d'Y_d \quad (A-56)$$

$$pd_9 := (v_d - x_d'i_q)pd_1 + (v_q + x_q'i_d)pd_2 \quad (A-57)$$

$$pd_{10} := Y_d(v_d - x_d'i_q) + Y_q(v_qx_qi_d) + i_q \quad (A-58)$$

$$pd_{11} := -\frac{1}{T_{do}'}(x_d - x_d')pd_1 \quad (A-59)$$

$$pd_{12} := -\frac{1}{T_{do}'} \quad (A-60)$$

$$pd_{13} := \frac{1}{T_{do}'} \quad (A-61)$$

$$pd_{14} := -\frac{1}{M}\omega_o pd_9 \quad (A-62)$$

$$pd_{15} := -\frac{1}{M}(pd_{15}f_1 + pd_{17}f_3 + pd_{10}pd_{19}) \quad (A-63)$$

$$pd_{16} := -\frac{1}{M}(pd_{16}f_1 + pd_{18}f_3 + pd_{10}pd_{20}) \quad (A-64)$$

$$pd_{17} := -\frac{1}{M}(pd_{10}pd_{21}) \quad (A-65)$$

$$pd_{18} := \frac{V_\infty}{Z_e}(R_2\cos(\delta) + X_1\sin(\delta)) \quad (A-66)$$

$$pd_{19} := \frac{V_\infty}{Z_e}(-X_2\sin(\delta) + R_1\cos(\delta)) \quad (A-67)$$

$$pd_{20} := (v_d - x_d'i_q)pd_{22} + 2(x_q - x_d')pd_1pd_2 + (v_q + x_qi_d)pd_{23} \quad (A-68)$$

$$pd_{21} := Y_q(x_q - x_d')pd_1 + Y_d(x_q - x_d')pd_2 + pd_2 \quad (A-69)$$

$$pd_{22} := Y_q(x_q - x_d')pd_1 + pd_2 + Y_d(x_q - x_d')pd_2 \quad (A-70)$$

$$pd_{23} := 2Y_q(1 + (x_q - x_d')Y_d) \quad (A-71)$$

$$u(t) = g(x(t), v(t)) := -\frac{L_f^3h}{L_gL_f^2h} + \frac{1}{L_gL_f^2h}v(t) \quad (A-72)$$

$$= \frac{-[[pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}]f - v(t)]}{[pd_{11}\ pd_{12}\ pd_{13}\ pd_{14}]g} \quad (A-73)$$