Journal of ELECTRICAL ENGINEERING, VOL. 62, NO. 5, 2011, 286–291

ROBUST POWER SYSTEM STABILIZER VIA NETWORKED CONTROL SYSTEM

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The paper presents a novel power system stabilizer (PSS) design for a multivariable power system. The proposed design procedure is based on the linear matrix inequalities and stabilization of controlled system with time-varying time delay.

K e y w o r d s: power system stabilizer (PSS), networked control systems (NCSs), time delay, Lyapunov-Krasovskii functional (LKF)

1 INTRODUCTION

Power system stabilizers are used to enhance damping of power system oscillations mainly through excitation control [3, 5, 7–10, 13]. Deregulation of the electricity markets has led to increasing uncertainties concerning the power flow within the network. PSSs are used to enhance damping of power oscillation. In the deregulation electricity market, the phenomenon of poorly damped low frequency inter-area power systems oscillations play an important role and it involves several groups of machines distributed over the different countries. There are several different ways how to improve the oscillation damping in a power system. As shown in references, improvement of inter-area oscillations damping can be advantageously accomplished with PSS. For multivariable power system obviously a typical PSS of the i-th synchronous generator (SG) consists of a gain and lead/lag compensation functions with π_i synchronous generator output feedback. Commonly used PSS, single inputs are shaft speed, terminal frequency, active power (current), terminal voltage and so on. Dual input PSS [9] normally use combinations of power or speed or frequency of the i-th SG to derive the stabilizing signal. PSS has decentralized structure.

In this paper, we introduce a novel approach to design of PSS using both classical stabilizing signal with decentralized structure and stabilizing signal which can be obtained from outputs of other SGs that is proposed novel PSS has no decentralized structure. Some idea about such PSS the reader can consults [12]. The data from other units of power system can be obtained using communication data network. Control system over data networks are commonly referred to as Networked Control Systems (NCSs). Integration of communication networks into feedback control loops inevitably leads to some problems. For the NCSs, the sampling data and controller signals are transmitted through a network. As results, it leads to a network-induced delay in a networked control closed-loop system. The existence of such a kind of delay in a network-based control loop can induce instability or poor performance of control systems [2, 5, 6]. In this paper, we consider that classical- decentralized stabilizing signal is already defined and problem is to design stabilizing signals obtained from other SGs which guarantee and improve closed-loop system stability, robustness and performances. In this paper, we do not study the problem of which kind of stabilizing signal could be used for complete PSS, but if this stabilizing signal is defined, we study the problem of stability, robustness and performance. The paper is organised as follows. Section 2 gives the preliminaries, definitions and problem formulation. Section 3 explains main results of the paper. And in Section 4, a numerical example is presented to show the design procedure of complete PSS.

Notation: Throughout this paper, for real matrix M, the notation $M \geq 0$ (respectively $M > 0$) means that matrix M is symmetric and positive semi-definite (respectively positive definite); "$*$" denotes a block that is readily inferred by symmetry; Matrices, if not explicitly stated, are assumed to have compatible dimensions.

2 PRELIMINARIES AND PROBLEM FORMULATION

Consider a set of L transfer function matrices identified in several different working points of power system. The working points are determined by steady state of power system with different power, voltages and so on, that are working points cover the whole range of system operation.

$$G^k(s) = \{G^k_{ij}\}_{m\times m}\,, \quad k = 1, 2, \dots, L \tag{1}$$

where

$$G^k_{ij}(s) = \frac{\Delta\Pi^k_i}{\Delta U^k_j}\,, \quad i, j = 1, 2, \dots, m\,.$$

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DOI: 10.2478/v10187-011-0045-8, ISSN 1335-3632

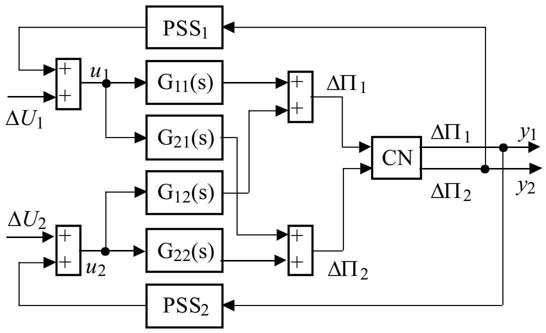

Fig. 1. Structure of complete PSS for the case of $m = 2$

$\Delta\Pi_i^k$ is the change of the i-th synchronous generator output for k-th experiment applied to the PSS input, ΔU_j^k is the change of the demand value of terminal voltage of j-th SG. We assume that all synchronous generators operate in the closed-loop with terminal voltage controller and decentralized structure PSS. The structure of SGs and complete PSS for the case of $m = 2$ is given in Fig. 1.

For the $PSS(s)$ design procedure, two models are used, [1] Model M_1:

$$PSS(s) = K_w \frac{sT_w}{1+sT_w} \frac{1+sT_{11}}{1+sT_{21}} \frac{1+sT_{12}}{1+sT_{22}} \cdots \frac{1+sT_{1r}}{1+sT_{2r}} \tag{2}$$

where all time constants T_{jk} are known. The problem is to design gain K_w and T_w.
Model M_2:

$$PSS(s) = \frac{sT_w}{1+sT_w} \begin{bmatrix} 1 & \frac{1}{1+sT_2} & \cdots & \frac{1}{1+sT_r} \end{bmatrix} \begin{bmatrix} K_{w1} \\ K_{w2} \\ \vdots \\ K_{wr} \end{bmatrix}. \tag{3}$$

Assume that all time constants T_j are known. The problem is to design $K_{w1}, K_{w2}, \dots, K_{wr}$ and T_w.

Combination of the two models different structures of PSS can be obtained. Model of power system (1) should be recalculated to following affine linear time-invariant continuous time uncertain systems.

$$\begin{aligned} \dot{x}(t) &= A(\xi)x(t) + B(\xi)u(t)\,, \\ y(t) &= Cs(t) \end{aligned} \tag{4}$$

where $x(t) \in R^n$ is the state vector, $u(t) \in R^m$ is the control input of closed-loop system, $y(t) \in R^l$ is the output of closed-loop system (Fig. 1). The matrices $A(\xi), B(\xi) \in S$ belong to convex hull, and S is a polytop with N vertices $S_1, S_2, \dots, S_N$ which can formally defined as

$$S := \left\{ \begin{matrix} A(\xi) \in R^{n\times n};\, B(\xi) \in R^{n\times m}\colon A(\xi) = \sum_{i=1}^N \xi_i A_i\,, \\ B(\xi) = \sum_{i=1}^N \xi_i B_i\,,\ \sum_{i=1}^N \xi_i = 1\,,\ \xi_i \ge 0 \end{matrix} \right\} \tag{5}$$

where A_i, B_i are constant matrices with appropriate dimensions and ξ_i are time-invariant uncertainties. Note S is a convex and bounded domain.

Consider the single PSS in the following form

$$PSS(s) = \frac{sT_w}{1+sT_w}\,. \tag{6}$$

The problem in this paper is to design two parameters K and T_w (structure M_1, M_2) such that for the PSS (7)

$$u_i(s) = \frac{K_{ij}s}{1+sT_{wij}} e^{-ts} y_j(s)\,,\ i \neq j\,;\ i,j = 1,2 \tag{7}$$

where the network induced delay in NCSs is given by $0 < \tau \le \tau_M$ and $\dot{\tau} \le \mu \le 1$, guarantees the stability, robustness and performance.

In the time domain, the PSS (7) can be reformulated as follow

$$u(t) = C_d W_f z(t) + C_d KCx(t) - C_d KC \int_{t-\tau}^t \dot{x}(s)\mathrm{d}s \tag{8}$$

where

$$\dot{z}(t) = -W_f z(t) + KCx(t) - KC \int_{t-\tau}^t \dot{x}(s)\mathrm{d}s \tag{9}$$

Consider $X(t) = \begin{bmatrix} x^\top(t) & z^\top(t) \end{bmatrix}^\top$ we obtain

$$u(t) = [C_d KC - C_d W_f]X(t) + [-C_d KC \quad 0] \int_{t-\tau}^t \dot{X}(s)\mathrm{d}s\,. \tag{10}$$

Substituting (10) to (4) will result to the closed-loop system

$$\dot{X}(t) - A_c X(t) + A_{dc} \int_{t-\tau}^t \dot{X}(s)\mathrm{d}s = 0 \tag{11}$$

where
$A_c = \begin{bmatrix} A + BC_d KC & -BC_d W_f \\ KC & -W_f \end{bmatrix}$, $A_{dc} = \begin{bmatrix} BC_d KC & 0 \\ KC & 0 \end{bmatrix}$.

Note that other part of PSS transfer function can be involved to power system transfer function matrix. The following performance index is associated with closed-loop system (4) and (7)

$$J = \int_0^\infty J(t)\mathrm{d}t\,,\ J(t) = X^\top(t)QX(t) + u^\top Ru(t) \tag{12}$$

where $Q = Q^\top > 0$, $R = R^\top > 0$ are matrices of compatible dimensions. Consider
$\eta(t) = \begin{bmatrix} \dot{X}^\top(t) & X^\top(t) & \int_{t-\tau}^t \dot{X}^\top(s)\mathrm{d}s & \int_{t-\tau_M}^{t-\tau} \dot{X}^\top(s)\mathrm{d}s \end{bmatrix}^\top$
and by substituting $u(t)$ from (10) to $u^\top(t)Ru(t)$ we obtain

$$u^\top Ru(t) = \eta^\top(t)K^\top RK\eta(t)$$

where

$$K = [\,0 \quad K_1 \quad K_2 \quad 0\,]\,,$$
$$K_1 = [\,C_d K C \quad -C_d W_{fd}\,]\,, \quad K_2 = [\,-C_d K C \quad 0\,]$$

then $J(t)$ can be rewritten as the following form

$$J(t) = \eta^\top(t) M_Q(\xi) \eta(t) \tag{13}$$

where

$$M_Q(\xi) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ * & K_1 R K_1 + Q & K_1 R K_2 & 0 \\ * & * & K_2 R K_2 & 0 \\ * & * & * & 0 \end{bmatrix}.$$

Associated with the cost of closed-loop system, the guaranteed cost controller is defined as follows:

DEFINITION 1. Consider the uncertain system (4) . If there exist a controller of the form (8) and a positive scalar J_0 such that for all uncertainties (5), the closed-loop system (11) is asymptotically stable and closed-loop value of the cost function (12) satisfies $J \le J_0$ then J_0 is said to be a guaranteed cost and the controller (8) is said to be guaranteed cost controller.

Finally we introduce the well known results from LQ theory.

LEMMA 1. *Consider the continuous-time delay system* (4) *with control algorithm* (8). *The control algorithm* (8) *is the guaranteed cost control law for the system* (4) *if and only if there exists LKF* $V(\xi, t)$ *such that the following condition holds*

$$\frac{d}{dt} V(\xi, t) + J(t) \le 0\,. \tag{14}$$

3 THE MAIN RESULTS

The following theorem provides robust stability and robust performance results for the closed-loop system (11).

THEOREM 1. *Consider the uncertain power system* (4) *controlled via NCSs with network-induced delay* τ *satisfying* $0 < \tau \le \tau_M$, $\dot\tau \le \mu \le 1$ *and the cost function* (12). *If there exist a controller of form* (8), *scalar* J_0, *and matrices* $P_i > 0$, $G_i > 0$, $G_{1i} > 0$, $G_{2i} > 0$ $(i = 1, \dots, N)$, N_1, N_2, N_3 *and* N_4 *that satisfy the following matrix inequality*

$$W_i = \begin{bmatrix} w_i^{11} & w_i^{12} & w_i^{13} & w_i^{14} \\ * & w_i^{22} & w_i^{23} & w_i^{24} \\ * & * & w_i^{33} & w_i^{34} \\ * & * & * & w_i^{44} \end{bmatrix} \le 0 \tag{15}$$

where

$$w_i^{11} = N_1 + N_1^\top + \tau_M G_{1i}\,,\; w_i^{12} = -N_1 A_{ci} + N_2^\top + P_i\,,$$
$$w_i^{13} = N_1 A_{dci} + N_3^\top\,, \quad w_i^{14} = N_4^\top\,,$$
$$w_i^{22} = -N_2 A_{ci} - A_{ci}^\top N_2^\top + \mu G_i + K_1^\top R K_1 + Q\,,$$
$$w_i^{23} = N_2 A_{dci} - A_{ci}^\top N_3^\top + (1-\mu) G_i + G_{2i} + K_1^\top R K_2\,,$$
$$w_i^{24} = -A_{ci}^\top + G_{2i}\,,$$
$$w_i^{33} = N_3 A_{dci} - A_{dci}^\top N_3^\top + (1-\mu) G_i - \frac{1}{\tau_M} G_{1i} - G_{2i} + K_2^\top R K_2\,,$$
$$w_i^{34} = A_{dci}^\top N_4^\top - G_{2i}\,,$$
$$w_i^{44} = -G_{2i} - \frac{1}{\tau_M} G_{1i}$$

then the uncertain system (4) *with controller* (8) *is asymptotically stable and the cost function* (12) *satisfies the following bound*

$$J \le J_0 = \sqrt{\lambda_{MP}^2 + \lambda_{MG}^2 + \lambda_{MG1}^2 + \lambda_{MG2}^2} * J_M \tag{16}$$

where

$$\lambda_{MP} = \underset{i=1\dots N}{\mathrm{Max}} (\mathrm{Max}(\mathit{Eigenvalue}(P_i)))\,,$$
$$\lambda_{MG} = \underset{i=1\dots N}{\mathrm{Max}} (\mathrm{Max}(\mathit{Eigenvalue}(G_i)))\,,$$
$$\lambda_{MG1} = \underset{i=1\dots N}{\mathrm{Max}} (\mathrm{Max}(\mathit{Eigenvalue}(G_{1i})))\,,$$
$$\lambda_{MG2} = \underset{i=1\dots N}{\mathrm{Max}} (\mathrm{Max}(\mathit{Eigenvalue}(G_{2i})))\,,$$
$$J_M = \Big\{ \|x_0\|^4 + \big(\int_{-t}^0 \|\varphi(s)\|^2 ds\big)^2 + \big(\int_{-\tau}^0 d\theta \int_\theta^0 \|\dot\varphi(s)\|^2 ds\big)^2 + \big(\int_{-\tau_m}^{-t} \|\varphi(s)\|^2 ds\big)^2 \Big\}^{1/2}$$

where $x(t) = \varphi(t)$, $t \in [-\tau_M, 0]$ *is a continuously differentiable initial function.*

P r o o f (S k e t c h). Take the Lyapunov-Krasovskii fucntional as follows

$$\begin{aligned} V(\xi, t) &= \sum_{i=1}^4 V_i(\xi, t)\,, \\ V_1(\xi, t) &= X^\top(t) P(\xi) X(t)\,, \\ V_2(\xi, t) &= \int_{t-\tau}^t X^\top(s) G(\xi) X(s) \mathrm{d}s\,, \\ V_3(\xi, t) &= \int_{-t}^0 \mathrm{d}\theta \int_{t+\theta}^t \dot X^\top(s) G_1(\xi) \dot X(s) \mathrm{d}s\,. \\ V_4(\xi, t) &= \int_{t-\tau_M}^t X^\top(s) G_2(\xi) X(s) \mathrm{d}s\,, \end{aligned} \tag{17}$$

Differentiating $V(\xi, t)$ with respect to time and using Newton-Leibnitz formula $x(t-\tau) = x(t) - \int_{t-\tau}^t \dot x(s) \mathrm{d}s$, we obtain

$$\dot V_1(\xi, t) = 2 X^\top(t) P(\xi) \dot X(t)\,,$$

$$\dot{V}_2(\xi,t)=\eta_1^\top(t)\begin{bmatrix}\mu G(\xi) & (1-\mu)G(\xi)\\ * & -(1-\mu)G(\xi)\end{bmatrix}\eta_1(t)\,,$$
$$\eta_2^\top=\begin{bmatrix}X^\top & \int_{t-\tau}^t\dot{X}^\top(s)\mathrm{d}s\end{bmatrix},$$
$$\dot{V}_3(\xi,t)\le\tau_M\dot{X}^\top G_1(\xi)\dot{X}(t)-$$
$$\frac{1}{\tau_M}\int_{t-\tau}^t\dot{X}^\top(s)\mathrm{d}sG_1(\xi)\int_{t-\tau}^t\dot{X}(s)\mathrm{d}s\,,$$
$$\dot{V}_4(\xi,t)\le\eta_2^\top(t)\begin{bmatrix}0 & G_2(\xi) & G_2(\xi)\\ * & -G_2(\xi) & -G_2(\xi)\\ * & * & -G_2(\xi)\end{bmatrix}\eta_2(t)\,,$$
$$\eta_2^\top(t)=\begin{bmatrix}X^\top(t) & \int_{t-\tau}^t\dot{X}^\top(s)\mathrm{d}s & \int_{t-\tau_M}^{t-\tau}\dot{X}^\top(s)\mathrm{d}s\end{bmatrix}.$$

Applying the free-weighting matrices technique, equation (8) is represented in the following equivalent form

$$\alpha(t)=2\eta^\top(t)\,[\,N_1^\top\quad N_2^\top\quad N_3^\top\quad N_4^\top\,]^\top\times[\,M_d(\xi)\quad -A_c(\xi)\quad A_{dc}(\xi)\quad 0\,]\,\eta(t)=0\,.$$

After manipulation with the above equation, we obtain

$$\alpha(t)=\eta^\top(t)M_\alpha(\xi)\eta(t)=0 \tag{18}$$

where

$$M_\alpha(\xi)=\begin{bmatrix}N_1+N_1^\top & -N_1A_c(\xi)+N_2^\top & N_1A_{dc}(\xi)+N_3^\top & N_4^\top\\ * & -N_2A_c(\xi)-A_c^\top(\xi)N_2^\top & N_2A_{dc}(\xi)-A_c^\top(\xi)N_3^\top & -A_c^\top(\xi)N_4^\top\\ * & * & N_3A_{dc}(\xi)+A_{dc}^\top(\xi)N_3^\top & A_{dc}^\top(\xi)N_4^\top\\ * & * & * & 0\end{bmatrix}$$

Because of $\alpha(t)=0$, thus

$$\dot{V}(\xi,t)=\sum_{i=1}^5\dot{V}_i(\xi,t)+\alpha(t)\le\eta^\top(t)[M_\alpha(\xi)+M_V(\xi)]\eta(t) \tag{19}$$

where

$$M_V(\xi)=\begin{bmatrix}\tau_MG_1(\xi) & P(\xi) & 0 & 0\\ * & \mu G(\xi) & (1-\mu)G(\xi)+G_2(\xi) & G_2(\xi)\\ * & * & -(1-\mu)G(\xi)-G_2(\xi) & -G_2(\xi)\\ * & * & * & -G_2(\xi)-\frac{1}{\tau_M}G_1(\xi)\end{bmatrix}.$$

Due to Lemma 1, the closed-loop system (6) is robustly asymptotically stable and gives an upper bound (a guaranteed cost) for the cost function (7) if

$$\dot{V}(\xi,t)+J(t)\le\eta^\top(t)W(\xi)\eta(t)\le 0 \iff W(\xi)\le 0\,. \tag{20}$$

$$W(\xi)=\sum_{i=1}^N=\xi_iW_i=M_\alpha(\xi)+M_V(\xi)+M_Q(\xi)=\begin{bmatrix}w^{11}(\xi) & w^{12}(\xi) & w^{13}(\xi) & w^{14}(\xi)\\ * & w^{22}(\xi) & w^{23}(\xi) & w^{24}(\xi)\\ * & * & w^{33}(\xi) & w^{34}(\xi)\\ * & * & * & w^{44}(\xi)\end{bmatrix},$$

$$w^{11}(\xi)=\sum_{i=1}^N\xi_iw_i11=N_1+N_1^\top+\tau_MG_1(\xi)\,,$$
$$w^{12}(\xi)=\sum_{i=1}^N\xi_iw_i12=-N_1A_c(\xi)+N_2^\top+P(\xi)\,,$$
$$w^{13}(\xi)=\sum_{i=1}^N\xi_iw_i13=N_1A_{dc}(\xi)+N_3^\top\,,$$
$$w^{14}(\xi)=\sum_{i=1}^N\xi_iw_i14=N_4^\top\,,$$
$$w^{22}(\xi)=\sum_{i=1}^N\xi_iw_i22=-N_2A_c(\xi)-A_c^\top(\xi)N_2^\top+\mu G(\xi)+K_1^\top RK_1+Q\,,$$
$$w^{23}(\xi)=\sum_{i=1}^N\xi_iw_i23N_2A_{dc}(\xi)-A_c^\top(\xi)N_3^\top+(1-\mu)G(\xi)+G_2(\xi)+K_1^\top RK_2\,,$$
$$w^{24}(\xi)=\sum_{i=1}^N\xi_iw_i24=-A_c^\top(\xi)N_4^\top+G_2(\xi)\,,$$
$$w^{33}(\xi)=\sum_{i=1}^N\xi_iw_i33=N_3A_{dc}(\xi)+A_{dc}^\top(\xi)N_3^\top-(1-\mu)G(\xi)-\frac{1}{\tau_M}G_1(\xi)-G_2(\xi)+K_2^\top RK_2\,,$$
$$w^{34}(\xi)=\sum_{i=1}^N\xi_iw_i34=A_{dc}^\top(\xi)N_4^\top-G_2(\xi)\,,$$
$$w^{44}(\xi)=\sum_{i=1}^N\xi_iw_i44=-G_2(\xi)-\frac{1}{\tau_M}G_1(\xi)\,.$$

For each $W_i\le 0$, $i=1,\dots,N$, then $W(\xi)=\sum_{i=1}^N\xi_iW_i\le 0$, $\sum_{i=1}^N\xi_i=1$, $\xi_i\ge 0$. Therefore, $\dot{V}(\xi,t)\le -J(t)\le 0$ $(J(t)\ge 0)$, respectively $J(t)\le -\dot{V}(\xi,t)$. By integrating $J(t)\le-\dot{V}(\xi,t)$ we obtain

$$J\le-\int_o^\infty\dot{V}(\xi,t)\mathrm{d}t=V_0=X_0^\top P(\xi)X_0+\int_{-\tau}^0X^\top(s)G(\xi)X(s)\mathrm{d}s+\int_{-\tau}^0\mathrm{d}\theta\int_\theta^0\dot{X}^\top(s)G_1(\xi)\dot{C}(s)\mathrm{d}s+\int_{-\tau_M}^0X^\top(s)G_2(\xi)X(s)\mathrm{d}s\,.$$

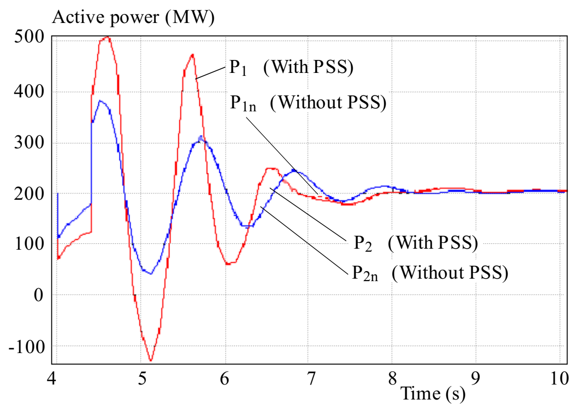

Fig. 2. Regulation of active powers by active power PSS output feedback

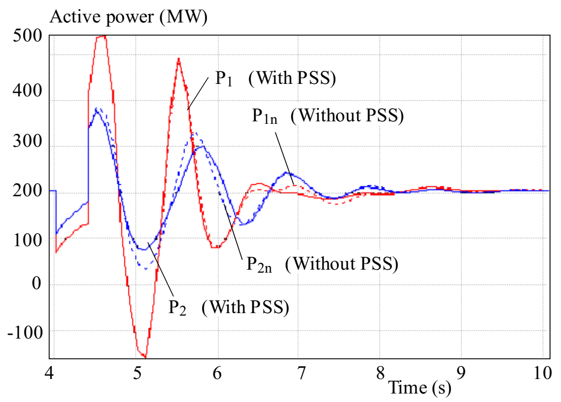

Fig. 3. Regulation of active powers by current PSS output feedback

Because of $X(t) = [\varphi^\top(t) \quad 0]$, $\forall t \in [\tau_M, 0]$ then

$$V_0 \le \lambda_{MP}\|x_0\|^2 + \lambda_{MG}\int_{-\tau}^{0}\|\varphi(s)\|^2\mathrm{d}s + \lambda_{MG1}\int_{-\tau}^{0}\mathrm{d}\theta\int_{\theta}^{0}\|\dot\varphi(s)\|^2\mathrm{d}s + \lambda_{MG2}\int_{-\tau_M}^{0}\|\varphi(s)\|^2\mathrm{d}s\,.$$

As we know that, for two arbitrary vectors $\boldsymbol{X}, \boldsymbol{Y}$, the following inequality is always held

$$\|VecX^\top \boldsymbol{Y}| \le \|\boldsymbol{X}\|\|\boldsymbol{Y}\|\,. \tag{21}$$

Consider

$$\boldsymbol{X} = \begin{bmatrix}\lambda_{MP}^\top & \lambda_{MG}^\top & \lambda_{MG1}^\top & \lambda_{MG2}^\top\end{bmatrix}^\top$$
$$\boldsymbol{Y} = \Big[\|x_0\|^2 \quad \int_{-\tau}^{0}\|\varphi(s)\|^2 \quad \int_{-\tau}^{0}\mathrm{d}\theta\int_{\theta}^{0}\|\dot\varphi(s)\|^2 \quad \int_{-\tau_M}^{0}\|\varphi(s)\|^2\mathrm{d}s\Big]^\top.$$

And applying the inequality (16), the upper bound cost function (7) J_0 is obtained as (11). Theorem 1. is proved.

4 EXAMPLE

Power system stabilizers (PSS) are used to enhance power system damping. The linearized mathematical model of the MIMO power system (1) has been obtained from experiments on the model of the Slovak Power System in the form given by Fig. 1. Experiment has been made for two SG's: EMO11 and EBO31 in one working point, that is $N = 1$. For above two SG's obtained transfer function matrix when $\Delta\Pi_i = \Delta P_i$, $i = 1, 2$ — active power of i-th SG, has been recalculated to the form of (4), where

$$A = \begin{bmatrix} A_{11} & 0 & 0 & 0\\ 0 & A_{12} & 0 & 0\\ 0 & 0 & A_{21} & 0\\ 0 & 0 & 0 & A_{22}\end{bmatrix}, \quad B^\top = \begin{bmatrix} B_{11} & 0\\ 0 & B_{12}\\ B_{21} & 0\\ 0 & B_{22}\end{bmatrix},$$
$$C^\top = \begin{bmatrix} C_{11} & 0\\ C_{12} & 0\\ 0 & C_{21}\\ 0 & C_{22}\end{bmatrix}, \quad D = 0,$$

$$A_{11} = \begin{bmatrix} 0 & 0 & -1.2905\\ 1 & 0 & -68.2416\\ 0 & 1 & -1.9819\end{bmatrix}, \quad B_{11} = \begin{bmatrix} 25.1311\\ -6.6692\\ 0.8847\end{bmatrix},$$
$$A_{12} = \begin{bmatrix} 0 & 0 & -106.1244\\ 1 & 0 & -74.3852\\ 0 & 1 & -6.2322\end{bmatrix}, \quad B_{12} = \begin{bmatrix} -83.08\\ 100.7547\\ 34.5436\end{bmatrix},$$
$$A_{21} = \begin{bmatrix} 0 & 0 & -35.2905\\ 1 & 0 & -48.187\\ 0 & 1 & -4.6111\end{bmatrix}, \quad B_{21} = \begin{bmatrix} -150.3434\\ 127.6829\\ 4.8710\end{bmatrix},$$
$$A_{22} = \begin{bmatrix} 0 & 0 & -1.2863\\ 1 & 0 & -68.2668\\ 0 & 1 & -2.4658\end{bmatrix}, \quad B_{22} = \begin{bmatrix} 10.0213\\ -3.1781\\ 0.3861\end{bmatrix},$$

$$C_{11} = C_{12} = C_{21} = C_{22} = [0 \quad 0 \quad 1]\,.$$

Assume that the simple PSS's are used with input active power variable, see Fig. 1. For the following three cases the gains and time constants are calculated:
$R = rI$, $Q = qI$, $P < p_{\max}I$,

a) $r = 1$, $q = 0.01$, $\tau_M = 0.001$ s, $\mu = 0.1$,
$$K = \begin{bmatrix} 0.0168 & 0\\ 0 & 0.021\end{bmatrix}, \quad T_w = \begin{bmatrix} 336.189 & 0\\ 0 & 454.268\end{bmatrix},$$

b) $r = 1$, $q = 0.1$, $\tau_M = 0.001$ s, $\mu = 0.1$,
$$K = \begin{bmatrix} 0.0089 & 0\\ 0 & 0.0174\end{bmatrix}, \quad T_w = \begin{bmatrix} 399.20 & 0\\ 0 & 899.194\end{bmatrix},$$

c) $r = 1$, $q = 0.1$, $\tau_M = 0.01$ s, $\mu = 0.9$,
$$K = \begin{bmatrix} 0.0076 & 0\\ 0 & 0.0172\end{bmatrix}, \quad T_w = \begin{bmatrix} 601.85 & 0\\ 0 & 594.841\end{bmatrix},$$

Dynamic behaviour of the active powers for three phase short circuits and $T = 0.4$ s, case a) on line V425 are given in Fig. 2. Figure 2 implies that non decentralized structure part of PSS practically does not increase the damper of closed-loop power system dynamic behaviour.

For the case when $\Lambda\Pi_i = IGEN_i$, $i = 1, 2$ and PSS with transfer function

$$PSS_i = \frac{k_i 0.1s}{1 + 0.1s}\frac{1 + 0.105s}{1 + 1.96s}$$

$$i = 1, 2,\ k_1 = 1.76,\ k_2 = 1.172\,.$$

The dynamic behaviours of active powers for three phase short circuits and $T = 0.4$ s on line V425 are given in Fig. 3. Figure 3 shows that there exist such SG variables which can be used for complete PSS and such way increases the damper of power system. Conditions of choice such variables are under research.

5 CONCLUSION

In this paper, a new approach to the complete robust PSS design has been proposed in time domain. We assume that stabilizing PSS variables are obtained through network communication system. Integration of communication networks into feedback control loops, inevitably leads to some problems.

As results, it leads to a network-induced delay in a networked control closed-loop system. The existence of such a kind of delay in a network-based control loop can induce instability or poor performance of control systems. In this paper sufficient robust stability conditions with guaranteed cost for such system are given. Theoretical results are supported with results obtained by solving robust PSS for two real power units working in Slovak Power System EMO11 and EBO31.

Acknowledgment

This work has been supported by the Slovak Grant Agency under Grant. No. 1/0544/09.

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Received 17 September 2010

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