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COMMUNICATIONS

PSS DESIGN VIA DISTURBANCE ATTENUATION METHOD

Vojtech Veselý — Ladislav Harsányi *

The use of a power system stabilizer (PSS) to control generator excitation systems is the most cost- effective method to damp low-frequency oscillation. This paper deals with a new method for the design of PSS based on the disturbance attenuation and LMI approach.

K e y w o r d s: interarea oscillations, PSS, power system

1 INTRODUCTION

Many types of oscillation phenomena can occur in present power systems. One is called local-mode oscillation: the oscillation of one or of a group of generators at a specific power plant has an influence on the system. The frequency of local-mode oscillation ranges from 0.7 to 2.2 Hz. Oscillations associated with several generators in one part of the system with respect to the rest of the system are referred to as inter-area oscillations. The frequency of these oscillations ranges from 0.1 to 0.7 Hz. The inter-area mode oscillations have a long history. They were observed in the tie-line connecting the large Pacific Southwest and the Pacific Northwest in the United States. It has been observed on the tie-line connecting the northern Midwest and Canada. Observations have also been made of low frequency oscillation at 0.4 Hz on the power system of Eastern Japan (Liu *et al*, 2003). Inter-area oscillation caused by a 1400 MW outage of block 2 Civeaux in France occurred on 4 April 2001. This inter-area oscillation was measured with a date logging system of the University of Stuttgart. As shown in (Kurth and Welfonder, 2003), damping of the inter-area oscillation by means of an aimed adjustment of the parameter sets is advantageously accomplished by power system stabilizers (PSS), speed controllers of steam or hydro power plants and by voltage controllers. The voltage controllers in the main parts of Europe and in the area of the German-French border, in the south of France as well as in Spain and Portugal have a strong damping effect on inter-area oscillations. A power system stabilizer may improve the damping of inter-area oscillation significantly. Another measure damp inter-area oscillations is to reduce the transient gain of the speed controllers in hydropower stations. If the transient gain does not remain small, there will occur a further undamping influence on the oscillation.

Unstable or poorly damped electromechanical oscillation modes in a power system cause not only stability problems. Thus is the main reason why a PSS has to be installed on generator sets to improve the system stability and guarantee the inter-area oscillation attenuation (Murgaš *et al*, 2004).

In this paper a novel approach to the PSS parameter design is proposed based on the disturbance attenuation (Boyd *et al*, 1994) and LMI approach.

2 PROBLEM FORMULATION

We are given a linear time-invariant model of the synchronous generator with all controllers and existing PSS in the form:

$$\dot{\boldsymbol{x}} = \mathbf{A}\boldsymbol{x} + \mathbf{B}_u\boldsymbol{u} + \mathbf{B}_w\boldsymbol{w} + \mathbf{B}_p\boldsymbol{p}\,, \tag{1}$$
$$\boldsymbol{z} = \mathbf{C}_z\boldsymbol{x}\,,\ \boldsymbol{y} = \mathbf{C}_y\boldsymbol{x}\,,\ \boldsymbol{y}_d = \mathbf{C}_d\boldsymbol{x}\,,\ \boldsymbol{p} = \Delta\boldsymbol{q}\,,\ \boldsymbol{q} = \mathbf{C}_q\boldsymbol{x}$$

where $\boldsymbol{x} \in R^n$, $\boldsymbol{u} \in R^m$, $\boldsymbol{w} \in R^d$, $\boldsymbol{p} \in R$ are the state, control, external disturbance and auxiliary variables, respectively, $\boldsymbol{z} \in R^{l_z}$, $\boldsymbol{y} \in R^l$, $\boldsymbol{y}_d \in R^{l_d}$ are the output, measurement output variable for P controller and measurement output for D (derivative) controller, and Δ is the uncertainty which satisfies the following inequality

$$\Delta^\top\Delta \le \mathbf{I}\,.$$

All matrices are constants with corresponding dimensions. Let us define the L_2 gain as the quantity

$$\sup_{\|\boldsymbol{w}\|_2\neq 0} \frac{\|\boldsymbol{z}\|_2}{\|\boldsymbol{w}\|_2} \le \gamma \tag{2}$$

where the L_2 norm of $\boldsymbol{w}$ is

$$\|w\|_2^2 = \int_0^\infty \boldsymbol{u}^\top\boldsymbol{u}\,\mathrm{d}t$$

and the supreme is taken over all nonzero trajectories of system (1) starting from $x(0) = 0$.

* Slovak Technical University, Faculty of Electrical Engineering and Information Technology, KASR, Ilkovičova 3, 812 19 Bratislava 1, Slovakia, E-mail: vesely@kasr.elf.stuba.sk; harsanyi@kasr.elf.stuba.sk

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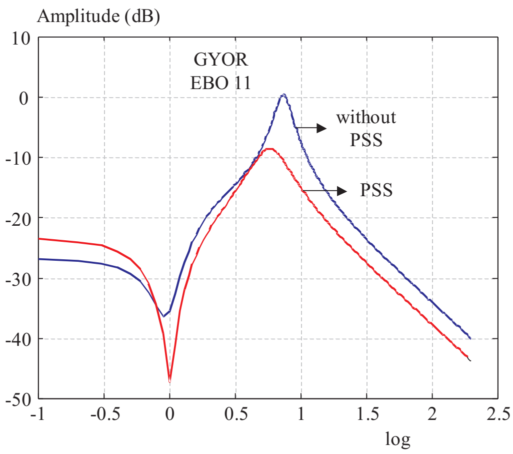

Fig. 1. BODE diagram of the system without and with designed PSS

The problem studied in this paper can be formulated as follows. Design the static output feedback

$$\boldsymbol{u} = \mathbf{K}_1\boldsymbol{y} + \mathbf{K}_2\boldsymbol{y}_d = \mathbf{F}\mathbf{C}\boldsymbol{x} \tag{3}$$

such that the closed-loop system (1) and (3) will be stable and γ has a minimal value.

3 PSS DESIGN

Suppose there exists a quadratic Lyapunov function $V = \boldsymbol{x}^\top\mathbf{P}\boldsymbol{x}$, $\mathbf{P} = \mathbf{P}^\top > 0$ (symmetric and positive definite matrix) and $\gamma \geq 0$ such that for all t and system (1) the following inequality holds (Boyd *et al*, 1994)

$$\frac{\mathrm{d}V}{\mathrm{d}t} + \boldsymbol{z}^\top\boldsymbol{z} - \gamma^2\boldsymbol{w}^\top\boldsymbol{w} \leq 0 \tag{4}$$

then the L_2 gain of the closed loop system is less than γ. For the closed loop system

$$\boldsymbol{x} = (\mathbf{A} + \mathbf{B}_u\mathbf{F}\mathbf{C})\boldsymbol{x} + \mathbf{B}_w\boldsymbol{w} + \mathbf{B}_p\boldsymbol{p} \tag{5}$$

and

$$\boldsymbol{p}^\top\boldsymbol{p} = \boldsymbol{q}^\top\Delta^\top\Delta\boldsymbol{q} \leq \boldsymbol{q}^\top\boldsymbol{q}$$

(6) for the time derivative of Lyapunov function V one obtains

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \boldsymbol{x}^\top(\mathbf{A}_c^\top\mathbf{P} + \mathbf{P}\mathbf{A}_c)\boldsymbol{x} + 2\boldsymbol{x}^\top\mathbf{P}(\mathbf{B}_p\boldsymbol{p} + \mathbf{B}_w\boldsymbol{w}) \tag{7}$$

where

$$\mathbf{A}_c = \mathbf{A} + \mathbf{B}_u\mathbf{F}\mathbf{C}\,.$$

Condition (4) holds if and only if $\mathbf{P} = \mathbf{P}^\top > 0$ and

$$\boldsymbol{x}^\top(\mathbf{A}_c^\top\mathbf{P} + \mathbf{P}\mathbf{A}_c)\boldsymbol{x} + 2\boldsymbol{x}^\top\mathbf{P}(\mathbf{B}_p\boldsymbol{p} + \mathbf{B}_w\boldsymbol{w}) + \boldsymbol{x}^\top\mathbf{C}_z^\top\mathbf{C}_z\boldsymbol{x} - \gamma^2\boldsymbol{w}^\top\boldsymbol{w} \leq 0 \tag{8}$$

holds for every $\boldsymbol{x}$, $\boldsymbol{w}$ and $\boldsymbol{p}$ satisfying

$$\boldsymbol{p}^\top\boldsymbol{p} - \boldsymbol{x}^\top\mathbf{C}_q^\top\mathbf{C}_q\boldsymbol{x} \leq 0\,. \tag{9}$$

(9) Using the S-procedure (Boyd *et al*, 1994), this is equivalent to existence of $\mathbf{P} > 0$, $\gamma > 0$, $\lambda > 0$ and $\mathbf{F}$ satisfying

$$\begin{bmatrix}\boldsymbol{x}^\top\\ \boldsymbol{p}^\top\\ \boldsymbol{w}^\top\end{bmatrix}^\top \begin{bmatrix}\mathbf{A}_c^\top\mathbf{P} + \mathbf{P}\mathbf{A}_c + \mathbf{C}_z^\top\mathbf{C}_z + \lambda\mathbf{C}_q^\top\mathbf{C}_q & \mathbf{P}\mathbf{B}_p & \mathbf{P}\mathbf{B}_w\\ \mathbf{B}_p^\top\mathbf{P} & -\lambda\mathbf{I} & 0\\ \mathbf{B}_w^\top\mathbf{P} & 0 & -\gamma^2\mathbf{I}\end{bmatrix} \begin{bmatrix}\boldsymbol{x}\\ \boldsymbol{p}\\ \boldsymbol{w}\end{bmatrix} \leq 0\,. \tag{10}$$

From equation (3) one obtains

$$\boldsymbol{u} = \mathbf{K}_1\mathbf{C}_y\boldsymbol{x} + \mathbf{K}_2\mathbf{C}_d\boldsymbol{x} = \mathbf{K}_1\mathbf{C}_y\boldsymbol{x} + \mathbf{K}_2\mathbf{C}_d(\mathbf{A}\boldsymbol{x} + \mathbf{B}_u\boldsymbol{u} + \mathbf{B}_p\boldsymbol{p} + \mathbf{B}_w\boldsymbol{w})$$

or

$$\boldsymbol{u} = \mathbf{F}_1\mathbf{C}_y\boldsymbol{x} + \mathbf{F}_2\mathbf{C}_d\mathbf{A}\boldsymbol{x} + \mathbf{F}_2\mathbf{C}_d\mathbf{B}_p\boldsymbol{p} + \mathbf{F}_2\mathbf{C}_d\mathbf{B}_w\boldsymbol{w} \tag{11}$$

where

$$\mathbf{F}_1 = \big(\mathbf{I} - \mathbf{K}_2\mathbf{C}_d\mathbf{B}_u\big)^{-1}\mathbf{K}_1,\ \ \mathbf{F}_2 = \big(\mathbf{I} - \mathbf{K}_2\mathbf{C}_d\mathbf{B}_u\big)^{-1}\mathbf{K}_2\,. \tag{12}$$

For a closed loop system one obtains

$$\boldsymbol{x} = \big(\mathbf{A} + \mathbf{B}_u\mathbf{F}_1\mathbf{C}_y + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d\mathbf{A}\big)\boldsymbol{x} + \big(\mathbf{I} + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d\big)\mathbf{B}_p\boldsymbol{p} + \big(\mathbf{I} + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d\big)\mathbf{B}_w\boldsymbol{w}\,.$$

Due to (10) and the above closed loop system we obtain the following BMI problem

$$\begin{bmatrix}\mathbf{A}_{pc}^\top\mathbf{P} + \mathbf{P}\mathbf{A}_{pc} + \mathbf{C}_z^\top\mathbf{C}_z + \lambda\mathbf{C}_q^\top\mathbf{C}_q & \mathbf{P}\big(\mathbf{I} + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d\big)\mathbf{B}_p & \mathbf{P}\big(\mathbf{I} + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d\big)\mathbf{B}_w\\ * & -\lambda\mathbf{I} & 0\\ * & 0 & -\gamma^2\mathbf{I}\end{bmatrix} \leq 0 \tag{13}$$

where $\mathbf{A}_{pc} = \mathbf{A} + \mathbf{B}_u\mathbf{F}_1\mathbf{C}_y + \mathbf{B}_u\mathbf{F}_2\mathbf{C}_d$, and $*$ denotes the transpose of the corresponding matrix.

Let us assume BMI problem (13) is feasible with respect to matrices $\mathbf{F}_1$, $\mathbf{F}_2$, $\mathbf{P} = \mathbf{P}^\top > 0$ and constants λ, γ. When matrices $\mathbf{F}_1$ and $\mathbf{F}_2$ are known, the gain matrices are

$$\mathbf{K}_2 = \mathbf{F}_2\big(\mathbf{I} + \mathbf{C}_d\mathbf{B}_u\mathbf{F}_2\big)^{-1}, \tag{14}$$

$$\mathbf{K}_1 = \big(\mathbf{I} - \mathbf{F}_2\mathbf{C}_d\mathbf{B}_u\big)\mathbf{F}_1\,. \tag{15}$$

If solutions of (14) and (15) exist, the closed loop system (5) is well posed and the gain matrices guarantee the closed loop system stability for all uncertainty given by inequality (6). The feasible solution of (13) guarantees disturbance attenuation at least with coefficient γ, that is

$$\|\boldsymbol{z}\|_2 \leq \gamma\|\boldsymbol{w}\|_2\,. \tag{16}$$

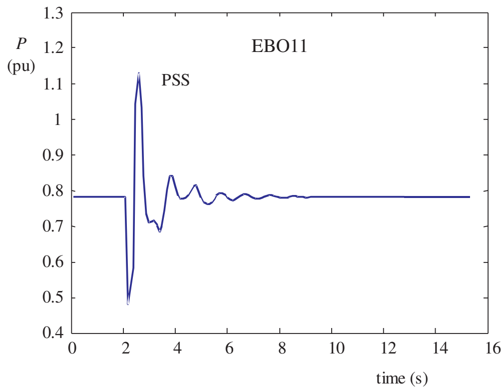

Fig. 2. Synchronous generator EBO11 active power change when a three-phase ground short circuit occurs on the middle of the line V283 for time $t = 0.2$ s with PSS.

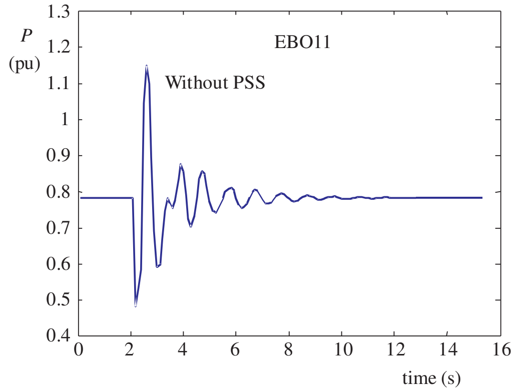

Fig. 3. Synchronous generator EBO11 active power change when a three-phase ground short circuit occurs on the middle of the line V283 for time $t = 0.2$ s without PSS.

4 EXAMPLE

Let inter-area oscillation come to the Slovak Power System from Györ. We are interested in PSS design with a static output feedback (3) which attenuates the above oscillation at least with γ (16) in the synchronous generator EBO11. The power system model (1) identified using the Slovak Power System model realized by MODES has the following parameters:

$$\mathbf{A} = \begin{bmatrix} -5.0778 & 1 & 0 \\ -50.2184 & 0 & 1 \\ -172.9247 & 0 & 0 \end{bmatrix}, \quad \mathbf{B}_u = \begin{bmatrix} 2.9487 \\ 161.073 \\ -179.4288 \end{bmatrix},$$

$$\mathbf{B}_p = \begin{bmatrix} -3.1509 & 0 & 0 \\ -8.7599 & 0 & 0 \\ -166.3205 & 0 & 0 \end{bmatrix}, \quad \mathbf{B}_w = \begin{bmatrix} -1.2692 \\ .3502 \\ -1.2574 \end{bmatrix},$$

$$\mathbf{C}_y = [1 \quad 0 \quad 0], \quad \mathbf{C}_z = \mathbf{C}_d = \mathbf{C}_y, \quad \mathbf{C}_q = \mathrm{diag}(1)_{3\times 3}$$

where $\boldsymbol{y} = \boldsymbol{y}_d = \Delta\mathbf{P}$ is the active power change of power station EBO11, u denotes the terminal voltage set point of EBO11, and the exogenous disturbance w has been modelled by adding a sinusoidal signal to the terminal voltage set point of the power station at Györ.

We have used the single PSS with the first derivative of active power of EBO11. The following results are obtained:

The eigenvalue of the closed loop system with designed PSS

$$1.2963 \pm 5.0259i, \quad 5.9676$$

and without PSS

$$.6339 \pm 6.7072i, \quad 3.8099.$$

The feedback gain for the first derivative of the active power is $\mathbf{K}_2 = -.0256$ s/p.u. and disturbance attenuation coefficient $\gamma = .9669$. The BODE diagram of the system without and with designed PSS is given in Fig. 1. It is clear that with PSS the maximal value of the closed loop transient gain is decreased by about 9 dB. For all frequencies $f > 0.125$ Hz, the closed loop system with designed PSS attenuates the disturbances better than without PSS. Figures 2 and 3 show the synchronous generator EBO11 active power change when a three-phase ground short circuit occurs on the middle of the line V283 for time $t = 0.2$ s with and without PSS.

5 CONCLUSION

In this paper a novel approach to the PSS parameter design is proposed based on the disturbance attenuation and LMI approach. The proposed method permits to design a robust PD type single or dual PSS for one or multimachine power system using the power system model obtained in an experimental way.

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