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A robust H$_\infty$ power system stabilizer design using reduced-order models

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Abstract

This paper deals with a robust H_∞ power system stabilizer (HPSS) design using reduced-order models to improve the damping oscillation in power systems. The stabilizer is dynamic, low order and robust. In order to obtain a reduced-order controller, the method of balanced truncation is used. Sufficient conditions in the form of two algebraic Riccati equations (AREs) and an upper bound explicitly characterize an H_∞ controller of lower dimensions. Furthermore, the bilinear transformation has been used to the design to prevent the pole-zero cancellation of the poorly damped poles and to improve the control system performance. The proposed technique is illustrated with applications to the design of stabilizer for a multi-machine power system. Simulation results under various operation conditions are given which show that the proposed HPSS damps the low-frequency oscillation in an efficient manner.

Keywords: H_∞ controller; Power system stabilizer design; Reduced-order models; Multi-machine power systems

1. Introduction

Power systems are complex non-linear systems and often exhibit low-frequency electromechanical oscillations due to insufficient damping caused by adverse operating conditions. Power system stabilizer (PSS) units have long been regarded as an effective way to enhance the damping of electromechanical oscillations in power system [1]. As a supplementary control to provide extra damping for synchronous generators, power system stabilizer (PSS) have been widely used in the electric power industry. Studies have shown that a well-tuned PSS can improve power system dynamic stability effectively. Over the past two decades, various control methods have been proposed for PSS design to improve overall system performance. Among these, conventional PSS of the lead-lag compensation type [1,2] have been adopted by most utility companies because of their simple structure, flexibility and easy of implementation. However, the performance of these stabilizers can be considerably degraded with the changes in the operating condition during normal operation. Most methods developed in recent years are based on well-developed modern control theory. These include: pole assignment [3–6], optimal control [7], self-tuning and adaptive control [6], variable structure control [8,9], rule-based and neural network based control [10–12]. The reduced order techniques [13,14] have been applied to the PSS design problem. The first one based on the LQR technique and the second one based on the iterative perturbation scheme. One of the principal disadvantages of these methods themselves is the lack of robustness.

In recent years, the standard H_∞ control problem has received increasing attention: for a given $\gamma > 0$, find all controllers such as that the H_∞ norm of the closed-loop transfer function is less than γ [21]. Practical power systems with PSS must be robust over a wide range of operating conditions. The developed H_∞ and related design methods lead to a fixed-structure and fixed-parameter, yet robust controller. Some research on applying H_∞ methods to PSS design is also presented in some publications [15–20] where the importance and the difficulties in the selection of weighting functions are reported. And also, the standard optimal H_∞ control method is known to obtain controllers of the same order as that of the open loop system [21]. Sufficient conditions in the form of two algebraic Riccati equations (AREs) and an upper bound explicitly characterize an H_∞ output feedback controller of lower dimensions.

In this paper, we present a robust reduced-order controller based power system stabilizer design to improve the damping oscillation in power systems. Then, the bilinear transformation is applied to the plant model to prevent the pole-zero

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cancellation and to deal with the ill conditioning problems that arise in the design process. The design method is implemented to a multi- machine power system. The performance of the proposed controller is examined and compared with both the CPSS and the standard H_∞ PSS (standard HPSS). Thus, the design of the proposed controller is simple and it is easy to implement.

The rest of the paper is organized as follows. A detailed description of the proposed design procedure is given in Section 2. The studied power system is given in Section 3. Simulation results are presented in Section 4 to demonstrate the effectiveness of the proposed method. Conclusions are drawn in Section 5.

2. The proposed controller design

2.1. Problem statements

Let us consider a linear system described by the state-space equations of the following form,

$$\dot{x} = Ax + Bu \tag{1}$$

$$y = Cx + Du$$

where $x \in R^n$ the state, $u \in R^m$ the control signal, $y \in R^q$ the output signal; and A, B, C and D are real matrices of appropriate dimensions. It is further assumed that given system is stabilizable and detectable, i.e. minimal [21].

We are interested in designing a dynamic output feedback controller of the form

$$\dot{x}_K = A_K x_K + B_K y \tag{2}$$

$$v = C_K x_K$$

where $x_K \in R^r$ the state, $v \in R^m$ the output signal for the controller; A_K, B_K and C_K are real matrices of the appropriate dimensions.

The model-order reduction problem consists of approximating a high-order system G by lower-order system G_r according to some given criterion. The structure of the overall system is given in Fig. 1, where G_r is reduced-order model, G_{γ_0} the modeling error and G_K the desired controller. The reduced-order model is unique from the input–output behavior point of view. As it is assumed that the stable part is an upper bounded, i.e. $||G_{\gamma_0}||_\infty \le \gamma_0$, therefore, H_∞-control tools can be used to find a stabilizing controller. Here the standard definition for H_∞-norm is given by

$$||G_{\gamma_0}||_\infty = \sup_\omega \sigma_{\max}[G(j\omega) - G_r(j\omega)] \tag{3}$$

where $\sigma_{\max}(\cdot)$ is the maximum singular value.

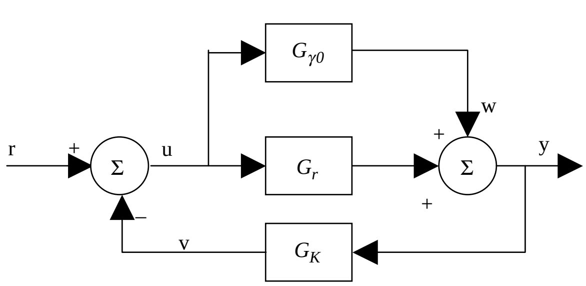

Fig. 1. Configuration of the closed-loop system.

2.2. Reduced-order model formulation

One way of obtaining a low order controller is to work with a low order system (plant). The standard optimal H_∞ control method is known to obtain controllers of the same order as that of the open loop system. Thus, if the full model of the system is used, the optimal H_∞ controller order will be unacceptably high. In order to reduce the order of the controller, we make use of the method of balanced truncation. We will present a brief outline of this procedure. The details of the balanced truncation algorithm can be found in [23–25].

Let (A,B,C,D) be an nth order stable system, but not necessarily minimal, state-space realization of the transfer function $G(s) = D + C(sI - A)^{-1}B$. The controllability and observability Grammians are defined as:

$$\bar{P} = \int_0^\infty e^{At} B B^T e^{A^T t} dt \tag{4}$$

$$\bar{Q} = \int_0^\infty e^{A^T t} C^T C e^{At} dt$$

The Hankel singular values Σ are defined as $\Sigma = \sqrt{\lambda(\overline{PQ})}$ where $\lambda(\overline{PQ})$denotes the eigenvalue of $\overline{PQ}$. Let $\bar{T}$ be a transformation for balanced realization with $x(t) = \bar{T} x_b$. Then the state space of balanced system can be expressed as:

$$\dot{x}_b = A_b x_b + B_b u \tag{5}$$

$$y_b = C_b x_b + D_b u$$

We partition the state vector x_b into two parts $[x_{b1}\ x_{b2}]^T$ where x_{b2} is the vector of the states that we wish to eliminate. Thus, Eq. (5) becomes:

$$\begin{bmatrix} \dot{x}_{b1} \\ \dot{x}_{b2} \end{bmatrix} = \begin{bmatrix} A_{b11} & A_{b12} \\ A_{b21} & A_{b22} \end{bmatrix} \begin{bmatrix} x_{b1} \\ x_{b2} \end{bmatrix} + \begin{bmatrix} B_{b1} \\ B_{b2} \end{bmatrix} u \tag{6}$$

$$y_b = \begin{bmatrix} C_{b1} & C_{b2} \end{bmatrix} \begin{bmatrix} x_{b1} \\ x_{b2} \end{bmatrix} + D_b u$$

The controllability and observability Grammians of the balanced truncation system are diagonal and satisfy the following equation:

$$\begin{bmatrix} A_{b11} & A_{b12} \\ A_{b21} & A_{b22} \end{bmatrix} \Sigma + \Sigma \begin{bmatrix} A_{b11} & A_{b12} \\ A_{b21} & A_{b22} \end{bmatrix}^T + \begin{bmatrix} B_{b1}B_{b1}^T & B_{b1}B_{b2}^T \\ B_{b2}B_{b1}^T & B_{b2}B_{b2}^T \end{bmatrix} = 0 \tag{7}$$