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Robust control of electrical power systems using PSSs and Bilinear Matrix Inequalities

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ABSTRACT

This work presents the application of Bilinear Matrix Inequalities to the robust adjustment of Power System Stabilizers with pre-defined structure. Results of some tests show that gain and zeros adjustments are sufficient to guarantee robust stability and performance with respect to various operating points. Making use of the flexible structure of BMIs, we propose an algorithm that guarantees a minimum damping factor specified for the closed loop system, always using a controller with flexible structure. The technique used here is the pole placement, whose objective is to place the poles of the closed loop system in a specific region of the complex plane. The BMIs are linearized using the homotopic method. Results of tests with a nine-machine system are presented and discussed, in order to validate the algorithm proposed.

1. Introduction

Robust control of electrical power systems considering the small signal modelling has been the subject of many researches during the last years. The importance of small signal stability studies is emphasized in [1]. H_∞ Control was applied to a single machine operating against an infinite bus in [2], while μ – synthesis was used to ensure robust stability and performance of electrical power systems in [3]. Techniques like LQG/LTR were also explored in [4].

Nevertheless, the most flexible technique in terms of grouping different requirements involves the use of Linear Matrix Inequalities (LMIs). LMIs have been used in many control applications [5], and as examples of their applications in electrical power systems we have [6–9]. In these papers, however, the controller generated by the LMI algorithm is full order; despite its practical importance to the power industry, the adjustment of Power System Stabilizers (PSSs) with pre-defined structure is handled only in [10].

Ref. [11] applies a H_∞ control technique called loop shaping with pole placement to the design of robust controllers for a 16-machine system. LMIs are used, in this case, to mix frequency domain specifications with time domain specifications. Other papers that apply H_∞ robust control to electrical power systems are [12,13]. These papers use FACTS devices to improve the stability and performance of the power system, and the controllers designed have the same order of the power system model.

Ref. [14] describes a method to design reduced order robust controllers for electrical power systems. Using LMIs and some linearizing parametrizations, it proposes an H_∞ optimization problem to obtain decentralized robust controllers. These controllers increase the power system damping, but this is not guaranteed in all cases since the optimization algorithm does not use pole placement constraints. Then, just stability is guaranteed.

Ref. [15,16] apply LMIs to robust pole placement for generic systems, but the controllers obtained are full order, and the formulation does not permit to choose the structure of the controller.

In [9], robust pole placement is performed together with H_∞ objectives through LMIs, using full order controllers. One of the drawbacks of this method is that the controller order increases with the order of the system when more sophisticated models are used. This same disadvantage affects other robust control methods, like μ-synthesis.

Ref. [10] applies LMIs to electrical power systems stabilization, pre-defining the structure of the controller and the controller poles. The results presented are related to a single machine-infinite bus system. The controller design is performed by using some results of [17].

Ref. [18] proposes a design method for robust controllers with pre-defined structure. The optimization problem formulated to

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design the controller is a BMI-problem (Bilinear Matrix Inequality). The BMI-problem is solved through a successive approximation algorithm. However, as the method does not use pole placement constraints explicitly, the controller obtained just guarantees the power system stability. The robust control formulation is based on H_∞ control.

Another work that uses BMIs to design robust controllers is [19]. In this paper, PSSs and controllers associated to HVDCs are obtained through a μ-synthesis based approach, which is used to initialize the decentralized controllers. Then, the problem is rewritten in the form of a BMI problem, which is solved through the homotopic method. Just the stability of the system is guaranteed – the method does not ensure a minimum damping for the power system poles.

Recent works that apply LMIs to generate robust controllers for power systems include [20], which applies a strategy known as multi agent system (hierarchized control structure) to improve stability of large scale power systems (the controllers design algorithm uses LMIs), [21], that integrates two control techniques to yield damping for low frequency oscillations in large power systems (it also employs FACTS), and [22], that applies LMIs to guarantee robust performance in load frequency control problems.

The main objective of this paper is to create a novel framework for power system pole placement in a desired region of the complex plane. A decentralized scheme with a pre-defined controller structure aiming to enhance the dynamic performance of the power system for various operating points is used. The controller structure flexibility is an important feature explored in this paper. At the same time, the use of LMIs and linearized BMIs permits to work with various operating conditions and specifications, which is an important characteristic of robust controllers.

The main advantage of using linearized BMIs instead of LMIs is that the first technique makes possible to deal directly with bilinear problems, with no need to perform changes of variables. These changes of variables can be very restrictive in some problems, even making the solution search by the algorithm infeasible.

The application of the proposed approach to a nine-machine system (New England–New York) is presented. In order to validate the controller obtained, nonlinear simulations are also performed. In Section 2, the power system model used in the paper and the closed loop system as well as its structure are presented. Section 3 depicts the development of the mathematical formulation for pole placement in a specified region of the complex plane considering various operating points. In Section 4, experimental results are shown and discussed. Finally, Section 5 presents the conclusions of this work.

2. Power system model and controller structure

PSSs are control devices whose function is to stabilize the unstable modes of the power system and increase the damping of its critical modes. The aim of stabilizing signals is to provide damping to the rotor oscillations through the generator excitation modulation. If the damping is increased, the stable power transfer limits are also increased, improving the power system performance. In order to yield damping, the PSSs must generate electrical torque components in phase with the rotor velocity variations.

The power system model to be described here is the one generally used in small signal stability studies [28]. The fundamental equations that describe the behavior of a power system, linearized around an operating point, are described in [23]. The generic model has the following form:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}\\ \mathbf{y} &= \mathbf{C}\mathbf{x}\end{aligned}, \tag{1}$$

where $\mathbf{x}$ is the state vector, $\mathbf{y}$ is the output vector (or measurements vector), and $\mathbf{u}$ is the input vector (or control vector). $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are matrices that define the dynamic linearized model of the power system.

The control policy adopted here consists on applying an output feedback to the system [24]. Moreover, the controller must have a decentralized structure, another important feature to be considered in electrical power systems due to the geographically disperse distribution of machines. Then, each PSS will be connected to a specific machine of the system, having as input the machine rotor speed; the output of the PSS is a control voltage to be applied to the corresponding machine.

In general the practical implementation of a controller with free structure is infeasible with the tools available in the power industry. On the other hand, if the usual structure defined by the following transfer function [24]:

$$K_i(s) = \frac{a_i s^2 + b_i s + c_i}{s^2 + (p_1 + p_2)s + p_1 p_2} \tag{2}$$

(where the poles $-p_1$ and $-p_2$ are chosen a priori) is adopted for the ith PSS, then its implementation can be immediate.

In this scheme with pre-defined poles, the controller design reduces to choosing the values of a_i, b_i and c_i, which define the gain and the zeros of the PSS. For the decentralized control scheme, the transfer function matrix of the controllers will assume the following form:

$$\mathbf{K}(s) = \begin{bmatrix} K_1(s) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & K_n(s) \end{bmatrix}, \tag{3}$$

where n is the number of machines of the power system, and each $K_i(s)$ has the structure given by Eq. (2).

The block diagram of the closed loop system is shown in Fig. 1. $\mathbf{K}(s)$ is the transfer function matrix of the PSSs (given by Eq. (3)), and $\mathbf{G}(s)$ is the transfer function matrix of the nominal power system. The input of $\mathbf{K}(s)$ is the vector $\boldsymbol{\omega}$ whose elements are the rotor speeds of each machine; the output of $\mathbf{K}(s)$ is the vector $\mathbf{V_S}$ whose components are the stabilizing signals for each machine. These signals are compared to reference voltages (components of the vector $\mathbf{V_{REF}}$), and the errors are applied to the input of the voltage regulators of each machine. The controllers $\mathbf{K}(s)$ (given by Eq. (3)) can be written in state space form as:

$$\begin{aligned}\dot{\mathbf{x}}_\mathbf{C} &= \mathbf{A_C}\mathbf{x_C} + \mathbf{B_C}\mathbf{y}\\ \mathbf{u} &= \mathbf{C_C}\mathbf{x_C} + \mathbf{D_C}\mathbf{y}\end{aligned} \tag{4}$$

There are many state space realizations for Eq. (3). Some of them can be found in [25].

Since the poles of the PSSs are given a priori, matrices $\mathbf{A_C}$ and $\mathbf{C_C}$ are pre-defined. Matrices $\mathbf{B_C}$ and $\mathbf{D_C}$ have a block diagonal structure whose elements contain the control problem variables (a_i, b_i and c_i).

Applying the controller of Eq. (4) to the system described by Eq. (1), the following state space description of the closed-loop system results:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{x}}_\mathbf{C} \end{bmatrix} = \begin{bmatrix} \mathbf{A} + \mathbf{B}\mathbf{D_C}\mathbf{C} & \mathbf{B}\mathbf{C_C} \\ \mathbf{B_C}\mathbf{C} & \mathbf{A_C} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{x_C} \end{bmatrix} \tag{5}$$

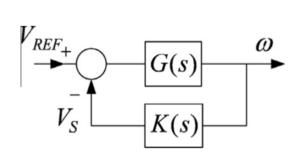

Fig. 1. Closed loop power system structure.