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Robust non-fragile power system stabilizer

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ABSTRACT

This paper presents a step towards the design of robust non-fragile power system stabilizers (PSSs) for single-machine infinite-bus systems. To ensure resiliency of a robust PSS, the proposed approach presents a characterization of all stabilizers that can guarantee robust stability (RS) over wide range of operating conditions. A three-term controller $(x_1 + x_2s)/(1 + x_3s)$ is considered to accomplish the design. Necessary and sufficient stability constraints for existing of such controller at certain operating point are derived via Routh–Hurwitz criterion. Continuous variation in the operating point is tackled by an interval plant model where RS problem is reduced to simultaneous stabilization of finite number of plants according to Kharitonov theorem. Controller triplets that can robustly stabilize vertex plants are characterized in a similar manner. The most resilient controller is computed at the center of maximum-area inscribed rectangle. Simulation results confirm robustness and resiliency of the proposed stabilizer.

Introduction

Power system stabilizers (PSSs) are often used to provide supplementary feedback stabilizing signals through the excitation systems. Therefore, the stability limit of power systems can be extended by PSSs which can enhance system damping at low frequency oscillations associated with electromechanical modes [1,2]. The conventional PSS commonly used in practice is a dynamic output feedback, a lead controller type, with a single or double stage and uses the speed deviation $\Delta\omega$ as a feedback signal [3]. Conventional fixed-parameter PSS may fail to maintain system stability over wide range of operating conditions or at least leads to a degraded performance once the deviation from the nominal point becomes significant. Consequently, design of robust PSSs becomes a priority to cope with uncertainties imposed by continuous variation in operating points. Synthesis of robust PSSs has been one of the most celebrated research areas in power system control. Over the past three decades or so, several methods have been developed that enable a PSS to cope with parametric uncertainties in the plant dynamics [4–11]. This is true for both types of uncertainties: structured and unstructured. A common divisor of these methods is that they rely on the celebrated YJBK parameterization [12] of all stabilizing controllers for a fixed linear time-invariant plant, which provides a free parameter over which an appropriate function of a closed-loop transfer function may be minimized. Elegant techniques for minimizing H_∞, H_2 and L_1 norms of different closed loop transfer functions have been developed using this parameterization [4,5]. Moreover, efficient numerical approaches have been subsequently developed [10,11]. Although these methods cope with uncertainty in the plant dynamics, they all assume that the derived parameters of a PSS are precise and exactly implemented. In practice it turns out, however that these gains cannot be implemented exactly (due to resistors' tolerance used with operational amplifiers implemented for continuous-time PSS) leading to fragility problem [13,14]. This raises an important issue that is a robust PSS can be very sensitive, or fragile, with respect to errors or perturbations in the controller coefficients and thus system instability may occur. In turn, that brings about a fundamental problem in robust control system design, which has been recently termed the fragility problem, and hence the design of non-fragile controller opens up as an important research topic that deserves further investigations. Continuous-time PSS implementation uses operational amplifiers with resistors having tolerances in the range of ±5% to ±20%. For discrete-time PSS implementation, imprecision is also expected in analog–digital and digital–analog conversion circuits. Consequently, PSS design has to be able to tolerate some uncertainty in the controller parameters as well as the plant dynamics. Fragility problem of a robust PSS in power system literature is a new topic except for [15]. Static output feedback design that permits for controller perturbation is suggested in [15] where speed deviation ($\Delta\omega$) and rotor angle deviation ($\Delta\delta$) are used for

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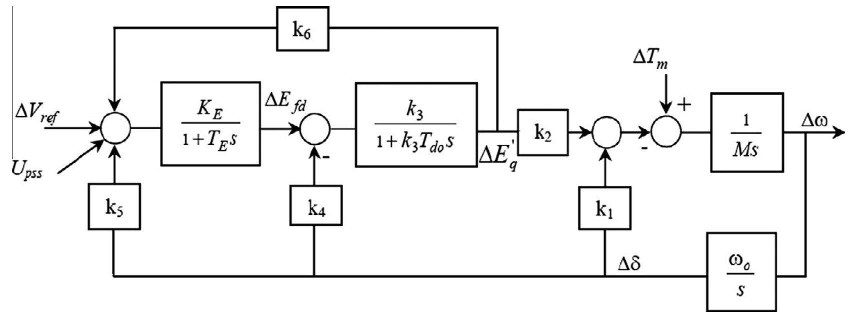

Fig. 1. Block diagram of the linearized model [1].

static feedback and two feedback gains have been computed. The feedback gain of $\Delta\omega$ can allow for a perturbation of +7.2% of its nominal values while that ($\Delta\delta$) has to be implemented exactly.

In this paper, the design of a robust and non-fragile PSS is presented to cope with uncertainties in power system dynamics and tolerate the perturbations in the PSS itself. To realize a robust first order PSS, necessary and sufficient stability conditions are derived using Routh–Hurwitz (RH) criterion. The stability boundaries derived by RH criterion are then plotted in the controller parameter-plane ($x_1 - x_2$) with fixed x_3 where the stability region is examined. Thereafter, the PSS pole time constant is allowed to vary over the typical range considered in PSS industry. The intersection of stability regions at different operating points with $x_3 = [x_3^- \quad x_3^+]$ can help characterize all stabilizing controllers, if it exists. Eight Kharitonov vertex plants are computed for an interval plant model considered to capture all uncertainties in operating point. Thus, the aforementioned approach can be applied only eight times where intersection of stability regions can easily be examined. Such graphical representation of the controller solution set can help select a point in the set such that its minimum distance to the region boundary is maximized, i.e. the center of the maximum-area inscribed rectangular.

The paper is organized as follows. Section 'Problem statement' describes the uncertainties of a simple power system. In Section 'Robust versus non-fragile: overview', an overview of robust and non-fragile control is presented. Necessary and sufficient constraints for characterizing all robust stabilizing PSSs are derived in Section 'Robust PSS design'. Selection of the most resilient PSS is reported in Section 'Non-fragility analysis'. Simulation results are considered in Section 'Simulation results'. Finally, Section 'Conclusion' concludes the paper.

Problem statement

The test system comprises a single-machine connected to an infinite-system through a tie lie line. Such infinite system may represent The venin's equivalent of a large interconnected power system. System dynamics are represented by four non-linear differential equations as given in [8]. Nonlinear model and data of the system are given in the Appendix A where the symbols are standard and have their usual meaning as given in [1]. The block diagram for linearized model of such system as proposed by deMello and Concordia [1] is shown in Fig. 1. The model parameters ($k_1, \ldots, k_6$) are load-dependent and have to be computed at each operating point given by active and reactive powers P, Q.

These parameters can be expressed as explicit functions in P and Q as derived in [8]. Open loop transfer function (TF) is in turn load-dependent and hence it is more convenient to accomplish the design. At any operating point, such TF has a general form given by:

$$G_p(s) = \frac{\Delta\omega}{\Delta U} = \frac{-b_1 s}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (1)$$

The coefficients a_0, a_1, a_2 and b_1 vary according to a vector ρ which consists of two independent quantities P and Q, i.e., $\rho = [P \quad Q]$ while a_3 and a_4 are always constant and independent of machine loading. Simply, any change in P, Q leads to corresponding changes in a_0, a_1, a_2 and b_1. Therefore, if P and Q vary over their prescribed intervals, i.e. $P \in [P^- \quad P^+]$ and $Q \in [Q^- \quad Q^+]$, Eq. (1) describes a family of plants rather than a nominal plant. Since a_0, a_1, a_2 and b_1 depend simultaneously on ρ, this family of plants can be approximated by an interval plant where:

$$a_4 = [\underline{a}_4 \quad \bar{a}_4], a_3 = [\underline{a}_3 \quad \bar{a}_3], a_2 = [\underline{a}_2 \quad \bar{a}_2], a_1 = [\underline{a}_1 \quad \bar{a}_1],$$
$$a_0 = [\underline{a}_0 \quad \bar{a}_0], b_1 = [\underline{b}_1 \quad \bar{b}_1] \quad (2)$$

where

$$[\underline{a}_i \quad \bar{a}_i] = [\min_{\substack{P\in[\underline{P} \quad \bar{P}],\\ Q\in[\underline{Q} \quad \bar{Q}]}} a_i / \max_{\substack{P\in[\underline{P} \quad \bar{P}],\\ Q\in[\underline{Q} \quad \bar{Q}]}} a_i], i = 0, 1, \ldots, 4$$

Robust stability of this interval plant implies that of the family of plants. However, instability of such interval plant does not imply instability of such family of plants. Stability of interval plants is often studied via Kharitonov theorem [12,16].

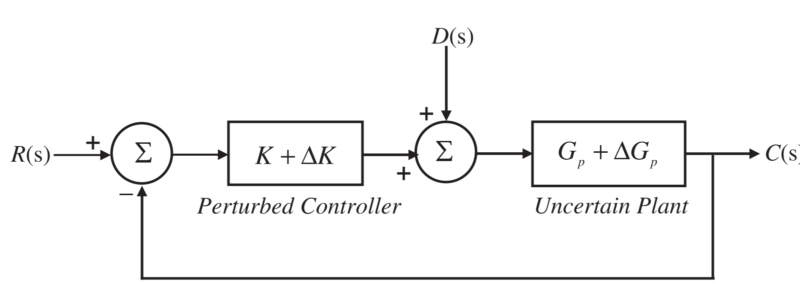

Fig. 2. Uncertain plant with perturbed controller.