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Parameterization of robust three-term power system stabilizers

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ABSTRACT

This paper addresses the problem of determining robust three-term output-feedback power system stabilizers (PSSs) $(C_1(s)=(x_1s+x_2+x_3/s)\,;\,C_2(s)=x_1(1+x_2s)/(1+x_3s))$ which can function properly over wide range of operating conditions. Necessary and sufficient constraints that characterize the admissible set of PSSs parameters are derived firstly by applying Routh-Hurwitz (RH) criterion to the characteristic polynomial of the generalized plant model. The complete set of stabilizing PSSs for any operating point is therefore determined in the controller parameter space $[x_1, x_2, x_3]$ by plotting RH constraints at this point. Since the design parameters are load-dependent and have to be adjusted at each operating condition, an interval plant is developed to describe uncertainties in the model parameters imposed by continuous variation in load patterns. Necessary and sufficient constraints for Hurwitz stability of such interval plant are derived using Kharitonov's theorem where robust PSS design is reduced to simultaneous stabilization of finite number of vertex/segment plants. The stability region for each of these plants is plotted using RH constraints where the intersection of the resulting stability regions yields the set of parameters that guarantee Hurwitz stability of the considered interval plant. Simulation results of an applicant PSS confirm the effectiveness of the proposed design approach.

1. Introduction

Power systems are often subjected to disturbances by several reasons such as continuous load changes, set-point changes, and faults. Consequently, it exhibit low frequency oscillations that either decay gradually, or continue to grow, causing system separation. These low frequency oscillations are due to the lack of damping of the electromechanical mode of the system [1–4]. The desired additional damping can be provided by supplementary excitation control through a power system stabilizer (PSS). The main problem encountered in the conventional PSS design is that power systems constantly experience changes in operating conditions due to variations in generation and load patterns. So, a conventionally designed PSS may fail to maintain stability over wide range of operating points. Further, the performance of conventional PSS is degraded once the deviation from the nominal point becomes significant. To cope with uncertainties, imposed by continuous variation in operating points, has become the priority of the PSS designers. To make the performance of a PSS robust, the design algorithm must account for power system uncertainties. Uncertainties in the power system model can be unstructured in the form of norm-bounded parameter uncertainty [5,6], or structured associated with loading and other varying operating conditions [7–11]. Various approximations have been utilized in the modeling of uncertain systems including μ-synthesis [7–11], Lyapunov state-space based procedures [12–15], and interval polynomial [16–20]. These approaches target two main objectives; the first considers the evaluation of system robustness under the effect of parametric uncertainties, while the second considers the synthesis of PSSs that can guarantee robustness under parametric uncertainties. In Refs. [7,8], Djukanovic et al. have successfully applied the structured singular value (SSV) theory to determine robust stability of a power system for a wide range of operating conditions. A systematic procedure for sequential design of decentralized controllers, in multimachine power system, was studied in Ref. [9] where the robust performance in terms of the structured singular value (SSV or μ) was used as the measure of control performance. Castellanos et al. [10,11] have examined the application of SSV theory to the problem of evaluating the robust stability of large power systems with structured uncertainties where variations in system operating conditions and system topology are modeled as structured uncertainties and included in the nominal power system model. Rao et al. [12] reduced the controller synthesis to solve a nonlinear optimization problem where parametric uncertainty was handled using Quantitative Feedback

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Nomenclature

All quantities are in per-unit unless otherwise stated

T_m	mechanical torque
T_e	electrical torque
V_T	terminal voltage
E'_q	voltage behind transient reactance
E_{fd}	field voltage
X'_d	generator *d*-axis transient reactance
X_d, X_q	direct axis and quadrature axis synchronous reactance
R_e, X_e	tie line resistance and reactance, respectively
δ	torque angle (rad)
K_E, T_E	exciter gain and time constant
P_g, Q_g	active and reactive power at generator bus
V^∞	infinite bus voltage
U_{pss}	stabilizing signal (PSS output)
M	inertia constant (s)
$k_1, \ldots, k_6$	parameters of the power system block-diagram
T'_{do}	open circuit *d-axis* time constant
ω_o	synchronous speed (rad/s)
$\Delta\omega$	rotor speed deviation
s	laplace operator
k_p, k_i, k_d	PID controller gains
K, T_1, T_2	parameters of a phase-lead compensator
$\underline{x}, \bar{x}$	lower and upper bounds of a variable *x*, respectively
$K^1, K^2, \ldots, K^4$	Kharitonov vertex polynomials
NS_i, $i = 1, \ldots, 4$	Kharitonov segments associated with $N_i(s)$, $i = 1,2, \ldots, 4$.
$G_s(s)$	family of Kharitonov segment plants
Δ_{ij}	polynomial characterizing the segment plant $G_{ij}(s, \lambda)$
$C(s)$	controller transfer function (TF)
$R_{31}, R_{21}, R_{11}, R_{01}$	Hurwitz residues for s^3, s^2, s^1, and s^0 rows
k_p^*, k_i^*	pre-specified values of k_p and k_i
k_i^{cr}, k_d^{cr}	critical values of the PID controller's parameters k_i and k_d.
$\varnothing$	empty set
ζ	damping ratio

Theory (QFT). In Ref. [13], the design of a robust decentralized state feedback PSSs was considered to guarantee pole-placement in a pre-specified region in the left-half of the complex plane. The design assumed full state measurability and considered polytopic uncertainty. Werner et al. [14] expressed the uncertainties due to variable operating points using Linear Fractional Transformation (LFT) and then an LMI technique is applied to find a 4th order H_∞ controller under regional pole placement constraints. Soliman et al. [15] suggested an iterative LMI algorithm to design robust decentralized PID based PSSs. In Ref. [16], Soliman suggested an interval arithmetic approach for computing the admissible set of robust proportional-derivative (PD) based PSS using interval Routh-Hurwitz arrays. The authors of Ref. [17] applied a generalized Kharitonov's theorem to parameter perturbations in the state space model of the power system with a PSS. The parameters of the PSS were considered as candidates for perturbations and the region of stability was computed using the edge theorem and the segment lemma. The design was carried out at certain operating point where only uncertainties in controller parameters are reported. In Ref. [18], uncertainties due to continuous variation in the operating point, was described by an interval polynomial. The design of a phase-lead PSS was reduced to simultaneous stabilization of eight vertex plants derived using Kharitonov's theorem. Root-locus technique was applied to compute only the gain where compensator's zero and pole time constants were pre-specified to ensure fast response. Rigatos and Saino [19] extended the results of Ref. [18] and presented the two-stage stabilizer. However, time constants of the compensator's poles and zeros were also pre-specified. Soliman et al. [20] presented a reconfigurable design of fault-tolerant PSS and FACTs controllers using Kharitonov's theorem where system uncertainties were represented by an interval polynomial. The gains of the controllers are computed using particle swarm optimization (PSO). The authors suggested an eigenvalue-based cost function that ensures a specific settling time. Computing the admissible set of robust phase-lead compensator's parameters, which can stabilize the plant under wide range of operating conditions, was not targeted in Refs. [17–20]. Furthermore, the case of PID based PSSs was not dealt with. In Refs. [21,22], robust PSS synthesis is reduced to a simultaneous stabilization of some operating points and then evolutionary algorithms such as genetic algorithms and particle swarm are applied to compute controller parameters while minimizing eigenvalue-based objective functions. Concisely, robust PSS design involves three basic issues regarding uncertainty modeling, controller order and solution algorithm. Robust PSS design techniques often result in a unique controller without considering the set of all admissible PSSs. Computing the set of admissible parameters gives great flexibility while implementing PSSs.

This paper presents a step to attack this problem by characterizing such set for a single-machine infinite-bus system. The robustness issue is treated using generalized Kharitonov theorem, while stability conditions derived with Routh-Hurwitz criterion are used to parameterize the stabilizing controllers. Two approaches are proposed for designing robust PID-based PSSs. The first one considers simultaneous stabilization of four segment plants while the second approach considers simultaneous stabilization of sixteen vertex plants. For phase-lead compensator design, simultaneous stabilization of only eight vertex plants is considered. The rest of the paper is organized as follows. Section 2 considers the challenge facing the design of PSSs and develops an interval plant model to capture all uncertainties imposed by loading conditions. Necessary and sufficient conditions for stabilizing an interval plant via a three-term controller using generalized Kharitonov theorem are briefly reviewed in Section 3. Parameterization of the robust PID-based PSS and that of robust phase-lead PSSs are presented in Sections 4 and 5, respectively. Section 6 presents the results while Section 7 concludes this work.

2. Problem formulation

The system under study comprises a single-machine connected to an infinite bus through a tie-line. Such system is commonly used in the analysis and design of a PSS. The system is represented by a fourth order linearized model as proposed by deMello and Concordia [3]. The linearized model of this system can be described by the block diagram shown in Fig. 1. The system data and nonlinear model are given in Appendix A.1. The model parameters k_1, k_2, k_4, k_5, k_6 shown in Fig. 1 depend basically on the values of *P and Q* while k_3 depends on the tie-line reactance only. These parameters could be expressed as explicit functions of *P* and *Q* as given in Ref. [18]. The state space realization of the system is given as follows:

$$\dot{x} = A(k)x + Bu, \quad y = Cx \tag{1}$$

where $x \in R^{4\times1}$ is the state vector defined by $x = [\,\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd}\,]^T$, u is the stabilizing signal and the output y is typically represented by the angular speed deviation