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ROBUST POWER SYSTEM STABILIZERS: A FREQUENCY DOMAIN APPROACH

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In this short paper a robust frequency domain-based approach to the power system stabilizer (PSS) parameter design is proposed. The principle of the proposed PSS design technique is the application of the sufficient condition for robust stability of uncertain systems in combination with direct controller synthesis.

K e y w o r d s: power system stabilizer, robust control, frequency domain

1 INTRODUCTION

Presently, there are two main aspects which allow to reduce the operating as well as the cold reserve power to be kept ready by individual network partners in order to maintain the power system reliability. First, the transmission lines, generators and loads are interconnected into large-scale and complex integrated systems. An important benefit brought about by the interconnected operation is that occurring power system disturbances, *eg* power plant failures, are jointly intercepted and temporarily compensated for by all participating power systems. Secondly, due to economy and consumers demands, multimachine power systems are being operated closer than ever to their stability limits.

Due to stochastically distributed switching actions, electromechanical transients continuously occur in electrical grids. They manifest themselves through local oscillations of individual generators or through interarea oscillations. In case of *local oscillations* (within the frequency range of 0.7–2.2 Hz) one or several local synchronous generators are involved. Oscillations associated with several generators in one part of the system with respect to the rest of the system are referred to as *interarea oscillations*. The frequency of these oscillations typically ranges from 0.1 to 0.7 Hz. *Multimodal* oscillations represent energy exchange between rotors and are characterized by low frequencies (around 0.1–0.2 Hz). Increased power transits are limited on one hand by thermal limit ratings of coupling lines and on the other hand by increasing endangering of the power system stability indicated by poorly damped or even increasing interarea oscillations [4]. Unstable or poorly damped electromechanical oscillation modes in a power system cause stability problems. As one of the most cost-effective methods of enhancing the stability and damping power swings in the power system, power system stabilizers (PSS) are added to the automatic voltage regulator (AVR) subsystem [2, 3, 4, 5, 6].

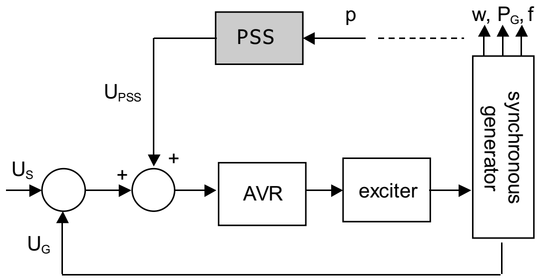

Fig. 1. PSS — supplementary control loop for the AVR system

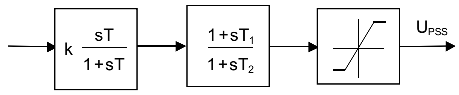

Fig. 2. Block scheme of a PSS

A considerable research effort is being devoted to the design of Power System Stabilizers (PSS). In general, the properties of a particular PSS depend on the choice of input quantities, the most commonly used being generator real power, current, rotor speed- or frequency deviation. Figure 1 depicts a supplementary PSS control loop for the AVR system.

There are a large number of PSS structures applied in practice. Typically, a PSS is a differentiating element with lead-lag corrective elements. One of the possible structures is in Fig. 2.

PSS designs are usually based on linearized system models where the actual PSS parameter settings depend on various quantities (generator load, impedance of transmission network, *etc*). However, as the system parameters may vary considerably during the operation, in the PSS parameters setting usually a trade-off has to be made.

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In this paper, a novel frequency domain robust approach to the PSS parameter design is proposed. The starting point for the robust control design is definition of a set of operating conditions for which the control has to be effective. For example, consider N various operating conditions determining N linearized models of the generator closed loop, obtained from experimental data measured in the power system under each of the N various operating conditions. Let each linearized model be a transfer function between the setpoint U_s and the change of an appropriately chosen generator output, denoted π in the closed loop generator — AVR (Fig. 1). The problem to be solved is to design a robust controller guaranteeing stability and a required performance for all N operating conditions represented by the N transfer functions.

The paper is organized as follows. Formulation of the problem to be solved is given in Section 2. Section 3 provides theoretical basis of the robust control frequency domain approach. A case study in Section 4 illustrates the proposed approach. Conclusions are deduced in the last Section 5.

2 PROBLEM FORMULATION

Consider a set of N transfer functions representing the N operating conditions

$$G_i(s) = \frac{\Delta\pi}{\Delta U_s} = \frac{B_i(s)}{A_i(s)} \qquad i = 1, 2, \dots, N \tag{1}$$

where

$A_i(s), B_i(s)$ are polynomials in the complex variable s,
$\Delta\pi$ is the deviation of a chosen generator output applied as the PSS input
U_s is the setpoint change of the closed-loop consisting of the generator under the AVR.

We want to design PSS parameters (k, T, T_1, T_2) guaranteeing stability and a required performance of the above specified system (1) in the whole prescribed operating range specified by means of the N transfer functions.

3 THEORETICAL BACKGROUND

3.1 Robust Stability (RS)

Linear time-invariant models describe actual plant dynamics only approximately. The "model uncertainty" can have several different sources, among others it occurs due to

1. linearization — the linearized process model is accurate only in the neighborhood of the reference state chosen for linearization,
2. different operating conditions — these can lead to changes in the parameters of the linear model.

Uncertainty associated with a physical system model can be described in many different ways. We will assume the controlled plant dynamics to be described in the frequency domain not by a single linear time-invariant model but by a family of plants. This approach assumes that the transfer function magnitude and phase at a particular frequency is not confined to a point but can lie in a disk region around this point. Algebraically, the family Π of plants is defined by

$$\Pi = \Big\{ G\colon\ \Big|\tilde{G}(j\omega) - G_N(j\omega)\Big| \le \ell_{am}(\omega) \Big\} \tag{2}$$

where $G_N(j\omega)$ is the nominal plant or the model defining the center of all disk-shaped regions, $\tilde{G}(j\omega)$ denotes any member of the plant family which satisfies

$$\begin{gathered} \tilde{G}(j\omega) = G_N(j\omega) + \ell_a(j\omega) \\ \text{with the bound} \quad |\ell_a(j\omega)| \le \ell_{am}(\omega)\,. \end{gathered} \tag{3}$$

Equation (3) is referred to as an additive uncertainty description.

In the complex plane, the family Π can be viewed as a "fuzzy" Nyquist plot, or a Nyquist band. To derive conditions for the robust stability of the whole set Π of plants defined by (3), the Nyquist stability criterion has been applied. According to it, it is first necessary that the nominal plant be closed-loop stable (stability of the nominal plant under the nominal controller is denoted nominal stability), then it is to ensure that the Nyquist band comprising all $\tilde{G}(j\omega) \in \Pi$ does not include the point $(-1, 0)$. Based on this consideration, the following theorem states the sufficient condition for robust stability (*ie* stability of the uncertain system under the nominal controller) [3].

THEOREM 1 (ROBUST STABILITY). *Assume that all plants $\tilde{G}$ in the family Π (2) have the same number of unstable poles and that a particular controller G_R stabilizes the nominal plant G_N. Then the system under the controller G_R is robustly stable if the nominal closed-loop transfer function $H(s) = \frac{G_N(s)G_R(s)}{1+G_N(s)G_R(s)}$ satisfies the following bound*

$$\left| H(j\omega)\frac{\ell_{am}(j\omega)}{G_N(j\omega)} \right| < 1 \quad \forall\omega\,. \tag{4}$$

P r o o f . If we factor the characteristic polynomial of the the uncertain system (3) in terms of the nominal system, we obtain (s is omitted for the sake of simplicity):

$$\begin{aligned} 1 + \tilde{G}G_R &= 1 + G_N G_R + \ell_a G_R \\ &= (1 + G_N G_R)\Big(1 + \frac{G_N G_R}{1 + G_N G_R}\frac{\ell_{am}}{G_N}\Big)\,. \end{aligned} \tag{5}$$

The first polynomial is actually the characteristic polynomial of the nominal system which, according to Thm. 1 is supposed to be stable. Applying the Small Gain Theorem [5] for the second term we obtain (4).

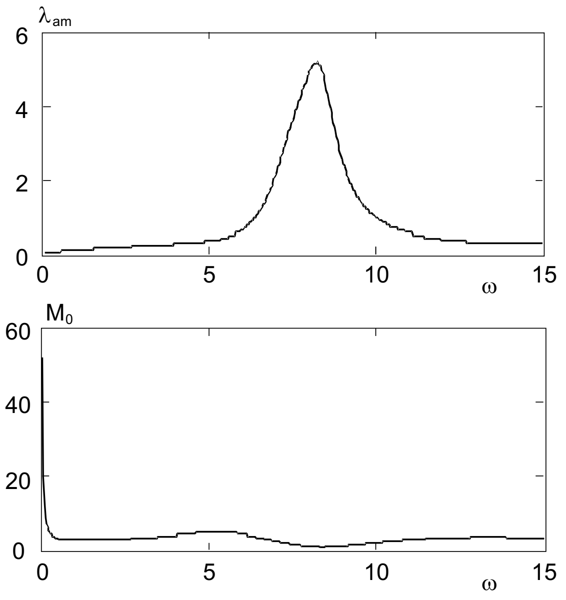

Fig. 3. Graphical representation of $\ell_{am}(\omega)$ and $M_0(\omega)$

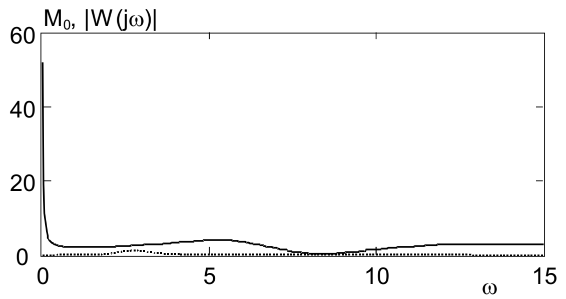

Fig. 4. Robust stability test for $W(s)$

Obviously, the term $\frac{\ell_{am}(j\omega)}{G_N(j\omega)}$ depends on plant description only and not on a particular controller.

For the rest of the paper the following notation will be adopted

$$\frac{1}{\frac{\ell_{am}(j\omega)}{|G_N(j\omega)|}} = M_0(\omega) \tag{6}$$

and for the design purpose the condition (4) will be used in the following form

$$|H(s)| < M_0(\omega) \qquad \forall\omega \tag{7}$$

$$\text{or} \qquad \left|\frac{G_N G_R}{1 + G_N G_R}\right| < M_0(\omega) \qquad \forall\omega\,. \tag{8}$$

Thus, to ensure stability of the considered uncertain system (3) in the whole operating range, a controller is to be designed which guarantees fulfillment of (8).

3.2 Uncertain System Modelling

To be able to apply the derived RS condition (7), it is necessary to have the uncertain systems described in the form (3). If the particular plant is specified by a set of N transfer functions (1), the nominal model is taken as the model of mean parameter values and the additive uncertainty is computed as the maximum of differences between the nominal model magnitude and magnitudes of each of the N transfer functions, evaluated for each frequency [2].

$$\ell_{am}(\omega) = \max_i \{||G_i(j\omega)| - |G_N(j\omega)||\} \quad \forall\omega \qquad i = 1, 2, \ldots, N\,. \tag{9}$$

4 CASE STUDY

In this case study, a PSS has been designed guaranteeing robust stability of the AVR subsystem (Fig. 1) in face of working point changes. As the controlled plant, a real power station operated within the Power System of the Slovak Republic has been considered. The N various operating conditions are represented by $N = 2$ different working points given by the synchronous generator active power output (220, 125) MW. System identification in these two working points yielded the following transfer functions:

1^{st} working point (220 MW):

$$\tilde{G}_1(s) = \frac{\Delta P_G(s)}{\Delta U_s(s)} = \frac{0.3672s^2 + 81.0413s - 21.1442}{s^3 + 6.646s^2 + 75.4311s + 387.122}, \tag{10}$$

2^{nd} working point (125 MW):

$$\tilde{G}_2(s) = \frac{\Delta P_G(s)}{\Delta U_s(s)} = \frac{-17.4847s^2 + 457.5781s - 172.9092}{s^3 + 64.1s^2 + 141.8s + 3217.4}. \tag{11}$$

The nominal model of mean parameter values (12) is stable with eigenvalues $(-33.737, -0.818 \pm 7.2633j)$

$$G_N(s) = \frac{G_1(s) + G_2(s)}{2} = \frac{-8.2451s^2 + 267.8097s - 97.0267}{s^3 + 35.4s^2 + 108.6s + 1802.3}\,. \tag{12}$$

Manipulating the transfer function (12) into the time constant form yields

$$G_N(s) = \frac{-0.0046s^2 + 0.1486s - 0.0538}{(0.02964s + 1)(0.1368^2 s^2 + 2 \times 0.1368 \times 0.1119 \times s + 1)}\,. \tag{13}$$

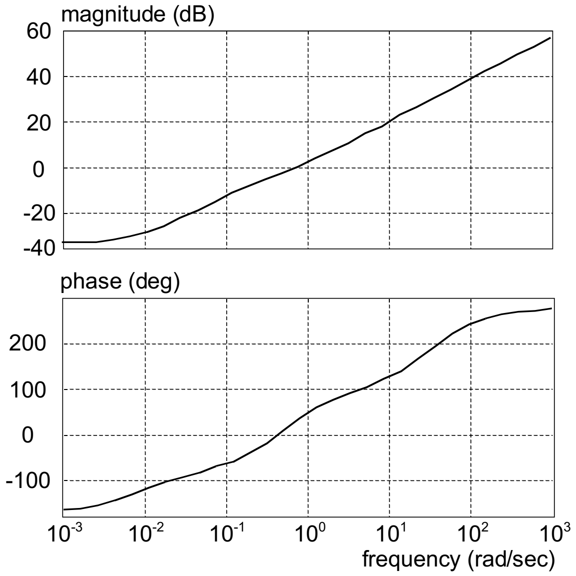

Fig. 5. Bode plots of the (ideal) PSS

According to (13), the damping factor of the nominal model is $b = 0.1119s$. A required performance improvement in terms of an increased $b = 0.4$ yields a desired (reference) transfer function

$$W(s) = \frac{-0.0046s^2 + 0.1486s - 0.0538}{(0.02964s+1)(0.1368^2s^2 + 2\times0.1368\times0.4\times s+1)}\,. \tag{14}$$

The plots of $M_0(\omega)$ and $\ell_{am}(\omega)$ obtained using (6) and (9), respectively, are depicted in Fig. 3, Fig. 4 shows the result of the stability robustness test (7) for the reference dynamics $W(s)$. As $|W(j\omega)| < M_0(j\omega)$ the closed-loop system is robustly stable.

To determine the PSS transfer function $G_R(s)$, the direct synthesis method has been applied. Comparing the closed-loop transfer function according to Fig. 1 with the reference $W(s)$ (15)

$$\frac{G_N(s)}{1 + G_N(s)G_{PSS}(s)} = W(s) \tag{15}$$

allows to express $G_R(s)$ guaranteeing robust stability of the controlled system:

$$G_{PSS}(s) = \frac{1}{W(s)} - \frac{1}{G_N(s)}\,. \tag{16}$$

Bode plots of the (ideal) PSS corresponding to (16) are depicted in Fig. 5.

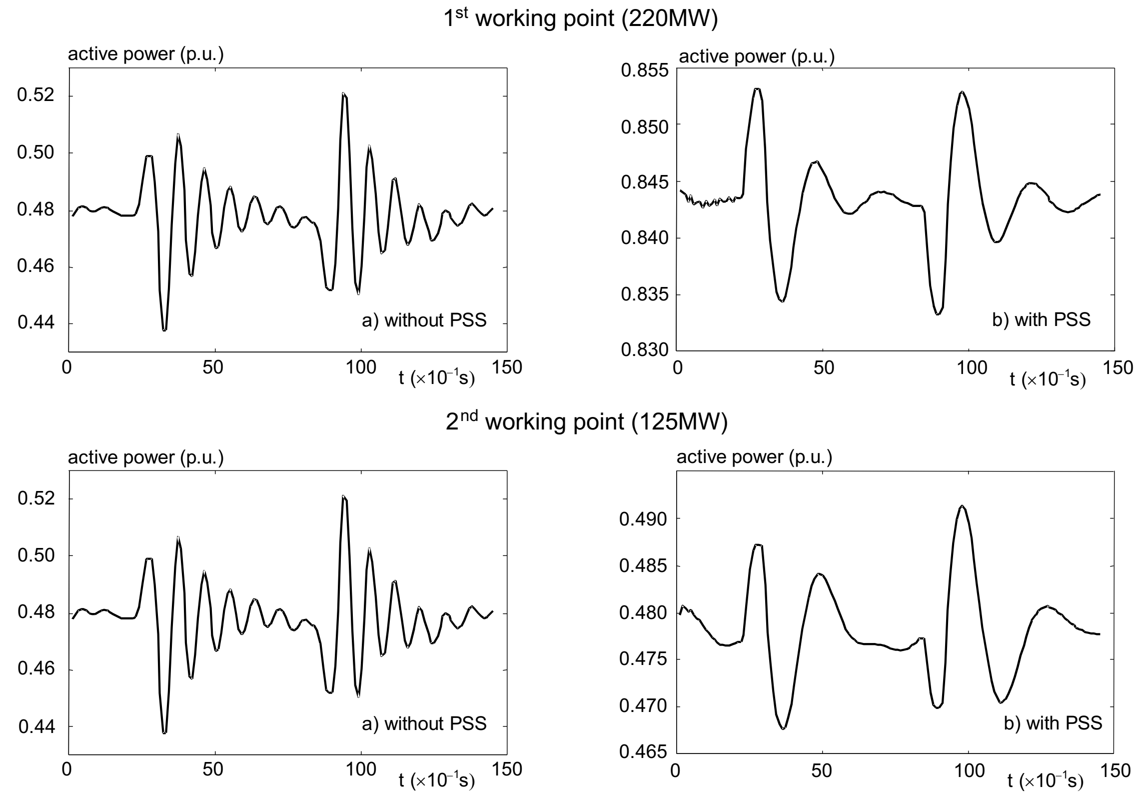

Fig. 6. Active power time responses to a 2.5 % step change in generator setpoint during 0.5 s for the both working points, with and without the designed PSS

Implementing the "ideal" PSS transfer function (16) would ensure an exact fulfillment of the required performance improvement. However, due to a fixed structure of the commercially available PSS's, the problem now reduces to finding real parameters of a fixed-structure PSS (17) which would approximate in the best possible way the Bode plots in Fig. 4.

$$G_{PSS}(s) = k\frac{Ts}{Ts+1}\cdot\frac{T_1 s+1}{T_2 s+1}\,. \tag{17}$$

The following results have been obtained applying the classical frequency domain approach:

$$k = -0.216\,, \quad T = 6s\,, \quad T_1 = 2s\,, \quad T_2 = 0.05s \tag{18}$$

The above design results have been verified using the model of the Power System of the Slovak Republic developed at the Department of Automatic Control Systems, FEI STU in Bratislava, under the program system MODES. The active power time responses to a 2.5 % step change in generator setpoint during 0.5 s for both working points (10), (11) are plotted in Fig. 6.

5 CONCLUSION

In this paper a novel frequency domain robust control based approach to the power system stabilizer (PSS) parameter design has been proposed. Sufficient condition for robust stability has been derived, which underlies the proposed PSS design procedure. A combination of robust control strategy and direct controller synthesis allows to incorporate performance requirements in the design. The design results have been verified using the model of the Power System of the Slovak Republic developed at the Department of Automatic Control Systems, FEI STU in Bratislava, under the program system MODES. The obtained responses have proved a significant beneficial effect of the PSS on damping and the active power oscillation amplitudes as well.

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