Design of Robust PSS Controllers in the Frequency Domain

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1. Abstract

In this paper a novel approach to the power system stabilizers (PSS) parameter design is proposed, based on the frequency domain approach to the robust control design. Sufficient condition for robust stability of uncertain systems is given which underlies the proposed PSS design procedure. Its combination with the direct controller synthesis allows to incorporate performance requirements in the design.

Keywords: power system stabilizer, robust control, frequency domain

2. Introduction

The tendency in electricity production is moving towards interconnected networks of transmission lines, generators and loads linked into very large and complex integrated systems. Nowadays, due to economy and consumers demands, multimachine power systems are being operated closer than ever to their stability limits. An important benefit brought about by the interconnected operation is the fact that occuring power system disturbances, e.g. power plant failures, are jointly intercepted and temporarily compensated for by all participating power systems. Both the above-mentioned aspects allow to reduce both the operating and cold reserve power needed to be kept ready by individual network partners in order to maintain the power system reliability. In electrical grids, electromechanical transients continuously occur due to stochastically distributed switching actions. They manifest themselves through local oscillations of individual generators or through interarea oscillations.

In the analysis of the different multimachine power system modes there is a distinction to be made between the local and the interarea modes. In case of *local oscillations* (within the frequency range of 0.7-2.2 Hz) one, two 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*. Frequency of these oscillations typically ranges from 0.1 to 0.7Hz. *Multimodal* oscillations represent energy exchange between rotors and are characterized by low frequencies (around 0.1- 0.2 Hz). For increased power transits, there are some limitations: on one hand, those given by thermal limit ratings of coupling lines and, on the other hand mainly increasing endangering of the power system stability which is indicated by poorly damped or even increasing interarea oscillations which can lead to much stronger limitation of the power transit than thermal limit ratings [4]. Unstable or poorly damped electromechanical oscillation modes in a power system cause stability problems. This is the main reason why stabilizers need to be installed on generator sets to improve the system stability [2, 3, 4, 5, 6].

Considerable research effort has been devoted to the design of Power System Stabilizers (PSS). In general, properties of a particular PSS depend on the choice of input quantities the most commonly used being generator active power, generator current, speed deviation and frequency deviation. A PSS block diagram is shown in Fig.1.

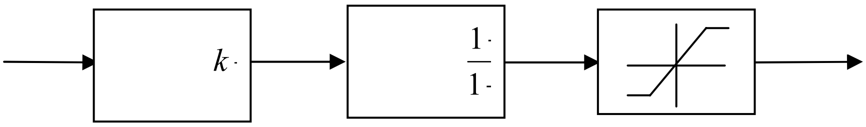

Fig.1. Block scheme of a PSS

Usually, the PSS designs are based on linearized system models. Actual PSS parameter settings depend on 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 is to be made.

In this paper a novel approach to the PSS parameter design is proposed.based on the frequency domain approach to the robust control design. The starting point of a robust control design is the definition of a set of operating conditions for which the control has to be effective. Consider for example N operating conditions. Then, from experimental data measured in the power system, N linearized models of the generator closed loop can be obtained, for each operating condition, thus yielding a set of N transfer functions. Each linearized model is expressed as a transfer function from the setpoint U_{sp} of the generator closed loop under automatic voltage regulator, to the change of the appropriately chosen generator output, denoted π, which is the input to the PSS. The problem to be solved is to design a robust controller guaranteeing stability and required performance for all N operating conditions represented by 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 basics of the frequency domain approach to the robust controller design. A case study in Section 4 illustrates the proposed approach. The conclusions are deduced in the last Section 5.

3. Problem formulation

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

68 (1)
68

where

$A_i(s)$, $B_i(s)$ are polynomials in the complex variable s,

$\Delta\pi$ is a chosen generator output used as the PSS input

ΔU_{sp} is the setpoint change of the closed-loop consisting of the generator under the voltage controller.

We want to design a controller guaranteeing stability and a required performance of the control plant for the whole operating range given by the set of N transfer functions.

4. Theoretical background

4.1. Robust Stability (RS)

Linear time-invariant models describe actual plant dynamics only approximately. The „model uncertainty“ can have several different sources, among others they are 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. To account for the model uncertainty we will assume the plant dynamics to be described not by a single LTI model but by a family of plants in the frequency domain. 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

$$\Pi = \left\{G : \left|\tilde{G}(j\omega) - G_N(j\omega)\right| \le \lambda_{am}(\omega)\right\} \tag{2}$$

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

$$\tilde{G}(j\omega) = G_N(j\omega) + \lambda_a(j\omega) \quad \text{with the bound} \quad \left|\lambda_a(j\omega)\right| \le \lambda_{am}(\omega) \tag{3}$$

Eq. (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 Nyquist band. To derive conditions for the robust stability of the family Π of plants defined by (3) the Nyquist stability criterion is applied. First, it is necessary that the nominal plant be closed-loop stable (nominal stability under the nominal controller), then it is necessary to ensure that the Nyquist band which comprises 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 of the uncertain system under the nominal controller.

<u>Theorem 1 (Robust Stability)</u>: Assume that all plants $\tilde{G}$ in the family Π defined by (2) have the same number of unstable poles and that G_R stabilizes the nominal plant G_N. Then the system with G_R is robustly stable if the nominal closed-loop transfer function $H(s) = \dfrac{G_N(s)G_R(s)}{1+G_N(s)G_R(s)}$ satisfies the following bound

$$\left|H(j\omega)\frac{\lambda_{am}(j\omega)}{G_N(j\omega)}\right| < 1 \qquad \forall\omega \tag{4}$$

Proof: If we factore the closed-loop characteristic polynomial considering the uncertain system (3) in terms of the nominal system, we obtain (s is omitted for the sake of simplicity):

$$1 + \tilde{G}G_R = 1 + G_N G_R + \lambda_a G_R = (1 + G_N G_R)(1 + \frac{G_N G_R}{1 + G_N G_R}\frac{\lambda_{am}}{G_N}) \tag{5}$$

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

Obviously, the term $\frac{\lambda_{am}(j\omega)}{G_N(j\omega)}$ depends on plant description only and not on a particular controller. For the rest of the paper the following notation will be adopted

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

For the design, the condition (4) will be used in the following form

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

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 (7).

4.2. Uncertain System Specification

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 the magnitudes of each of the N transfer functions at each frequency [1].

$$\lambda_{am}(\omega) = \max_i \left\{ \big| |G_i(j\omega)| - |G_N(j\omega)| \big| \right\} \qquad \forall\omega, \qquad i = 1,2,\ldots,N \tag{8}$$

5. CASE study

In this case study, a PSS has been designed guaranteeing robust stability in face of working point changes for the plant represented by the closed-loop of the synchronous generator under a voltage controller. A real power station operated within the Power System of the Slovak Republic has been considered. Two different working points have been specified by the SG active power (220, 125) MW. Identification in these two working points has yielded the following transfer functions:

1st working point (220MW):

$$\tilde{G}_1(s) = \frac{\Delta P_G(s)}{\Delta U_s(s)} = \frac{0.3672s^2 + 81.0413s - 21.1442}{s^3 + 6.646s^2 + 75.4311s + 387.122} \tag{9}$$

2nd working point (125MW):

$$\tilde{G}_2(s) = \frac{\Delta P_G(s)}{\Delta U_s(s)} = \frac{-17.4847s^2 + 457.5781s - 172.9092}{s^3 + 64.1s^2 + 141.8s + 3217.4} \tag{10}$$

The nominal model of mean parameter values and its time constant form are as follows

$$G_N(s)=\frac{-8.2451s^2+267.8097s-97.0267}{s^3+35.4s^2+108.6s+1802.3}=\frac{-0{,}0046s^2+0{,}1486s-0{,}0538}{(0{,}02964s+1)(0{,}1368^2s^2+2.0{,}1368.0{,}1119s+1)} \qquad (11)$$

The nominal model is stable with eigenvalues $(-33.737,-0.818\pm 7.2633j)$ and a damping factor $b=0.119s$. If b is to be increased to b_d = 0.4, which corresponds to a performance improvement, according to the direct controller synthesis we need to specify the required (reference) closed-loop transfer function as

$$W(s)=\frac{-0{,}0046s^2+0{,}1486s-0{,}0538}{(0{,}02964s+1)(0{,}1368^2s^2+2.0{,}1368.0{,}4s+1)} \qquad (12)$$

Fig. 2 shows the result of the stability robustness test (7) for the reference closed-loop $W(s)$. As $|W(j\omega)|<M_0(\omega)$ the closed-loop systems is robustly stable. To determine the PSS transfer function $G_R(s)$, the direct synthesis method has been applied. Comparing the transfer functions

$$\frac{G_N(s)}{1+G_N(s)G_R(s)}=W(s) \qquad (13)$$

allows to express W71hich, due to fulfillment of (7) will guarantees closed –loop robust stability

$$G_R(s)=\frac{1}{W(s)}-\frac{1}{G_N(s)} \qquad (14)$$

Bode plots of the required PSS determined from the reference dynamics W(s) are depicted in Fig. 3.

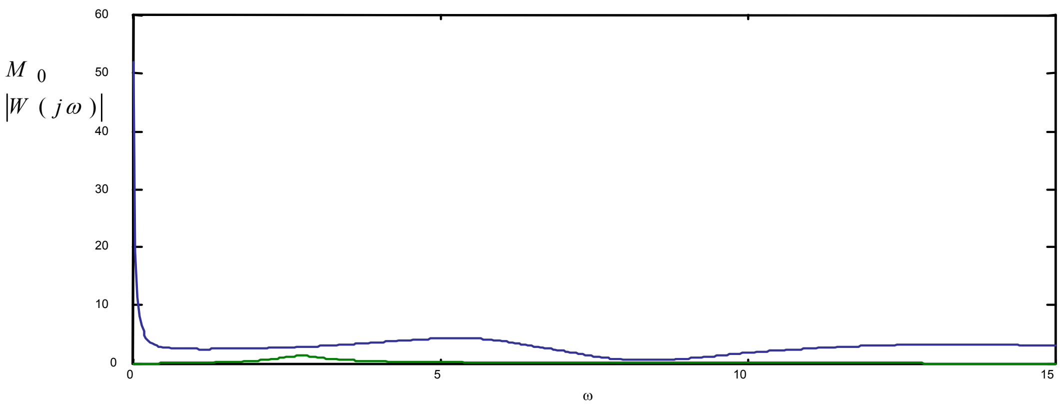

Fig. 2 Robust stability test: the upper plot - $M_0(\omega)$
the lower plot - $|W(j\omega)|$

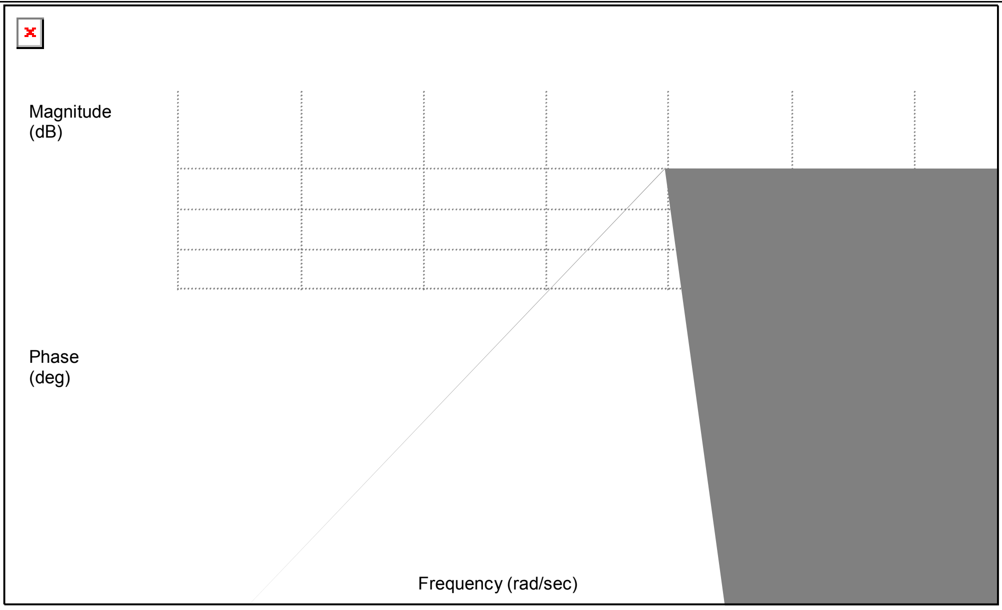

Fig. 3 Bode plots of the required PSS

The required PSS transfer function structure is

$$G_R(s) = k\frac{Ts}{Ts+1}\cdot\frac{T_1 s+1}{T_2 s+1} \tag{15}$$

With respect to Fig. 3, the following PSS parameter values have been determined:

$$k = -0.216,\quad T = 6s,\quad T_1 = 2s,\quad T_2 = 0.05s \tag{16}$$

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 active power time responses to a 2.5% step change in generator setpoint during 0.5s for the 2nd working point (10) without and with the designed PSS are in Fig. (4). A consideable improvement of the damping properties and a decrease in the active power oscillation amplitudes is evident.

a) without PSS

b) with PSS

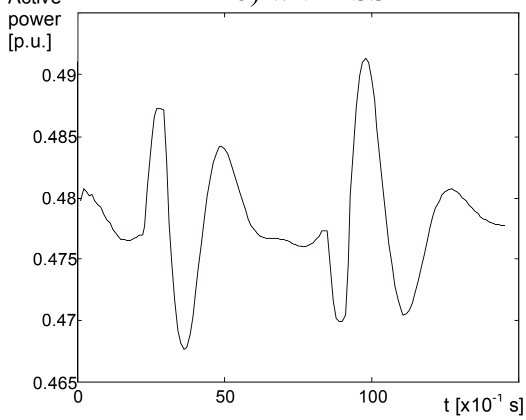

Fig. 4 Active power time responses to a 2.5% step change in generator setpoint during 0.5s in the 2nd working point (125MW)

6. Conclusion

In this paper a novel approach to the power system stabilizer (PSS) parameter design has been proposed, based on the frequency domain robust control approach. Sufficient condition for robust stability has been derived, which underlies the proposed PSS design procedure. A combination of robust control strategy and the 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 time responses have proved a significant effect of the PSS on damping and the active power oscillation amplitudes as well.

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